THE PRESERVATION OF ST. PAUL'S CATHEDRAL & OTHER FAMOUS BUILDINGS

WILLIAM HARVEY

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Frontispiece.

A General View of St. Paul's Cathedral from the South-West.

THE PRESERVATION OF ST PAUL'S CATHEDRAL & OTHER FAMOUS BUILDINGS

A TEXT BOOK ON THE NEW SCIENCE OF CONSERVATION, INCLUDING AN ANALYSIS OF MOVEMENTS IN HISTORICAL STRUCTURES PRIOR TO THEIR FALL

BY

WILLIAM HARVEY

Gold and Silver Medallist and Travelling Student, Schools of the Royal Academy. Lately Student of the British School at Athens

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PREFACE

ABLE men in the past have given the best that was in them to the work of preserving our architectural masterpieces, but their knowledge of the conservator's art was not always, or indeed often, equal to their creative ability and was restricted both by the fashion of the moment and by the state of structural science at the particular period in which they worked.

Preservation by patching with new material in the form of piers, props, stays, and buttresses has alternated with the so-called restoration of ancient buildings by the illogical processes of demolishing and rebuilding them in the same or even in a different style.

The conservation advocated in this book aims at the retention of the historic building, sound and whole, by means and methods scientifically devised and inconspicuously applied to meet the needs of the case in the most complete manner possible.

This science of conservation is of recent development, and has been evolved as a practical alternative to the demolition of ancient buildings or their disfigurement by extraneous patches and props.

Its fascinating interest is manysided, for archæological and structural researches must be combined with the invention of appropriate measures of repair, and the preliminary survey involves the exercise of qualities usually associated with the habits of the mountaineer or the steeplejack.

A taste for this adventurous study of ancient buildings and the curious manner of their decay had already resulted in the collection of a great deal of information on the subject when, in the spring of 1921, Mr. Macartney set me free to sketch and measure in St. Paul's Cathedral.

My examination of the fabric was undertaken in the course of a long inquiry into arched and vaulted construction, both at home and abroad, this subject having been my principal hobby for more than twenty years.

Comparison with other colossal structures in which I had studied enabled me to apprehend causes of danger at St. Paul's Cathedral that have been ignored by observers unfamiliar with the examination of arched structures, and, in the interests of the preservation of St. Paul's Cathedral, I

place the summary of my researches before my professional colleagues and the public.

The book is written, in popular form, to indicate how great arched buildings drift to their final collapse, and how optimistic custodians, unable to read the structural signs of approaching danger, permit them to do so and even assist in the process by injudicious repairs.

At St. Paul's Cathedral the marvel is that patchings carried out with Chinese diligence during the last two centuries have not already achieved the destruction that they have undoubtedly hastened.

There will come a time, however, when one such patching scheme will be the last that the weary building will endure.

Both in the writing of this book and in the long series of surveys in England and abroad, and in the experimental researches that went towards its making, I have received the enthusiastic assistance of my wife, who has encouraged me to devote my time to the study of historical buildings.

For his kind permission to take measurements in the Cathedral, and to publish the photograph, Fig. 4, and the drawing, Fig. 10, I have to thank Mr. Mervyn E. Macartney, B.A., F.S.A., Surveyor to the Fabric.

Mr. F. Chatterton, F.R.I.B.A., has given me the benefit of his long acquaintance with the building, and has also specially drawn the plan and sections, Figs. 32, 33 and 35.

To Mr. W. Godfrey Allen I am indebted for permission to publish his beautiful drawing, Fig. 12, showing the comparative sections of the "Old" and "New" St. Paul's, and to Mr. Harry Sirr, F.R.I.B.A., for the loan of the north elevation of Old St. Paul's, Fig. 16.

My thanks are also due to Mr. Rudolf Dircks, Editor of the "R.I.B.A. Journal," for the loan of the blocks illustrating my model of Westminster Hall roof, Figs. 61, 62, 63.

My son, J. H. Harvey, has assisted in making and testing the model, Figs. 64, 65, 66, and has drawn some of the diagrams. Among other illustrations from my photographs and sketches some have appeared in "The Architects' Journal," "The Builder," and "The Engineer," and for permission to reproduce them here I have to thank the publishers of these magazines.

WILLIAM HARVEY.

March, 1925.

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Wren's favourite design for St. Paul's.
(From a Model in the Cathedral.)

INTRODUCTION

TO Sir Christopher Wren and to his personal investigations and inventions, as well as to the established standard of his achievements in enduring stone, the constructional science of the present day owes many of its good qualities and some of the brightest of its leading ideas.

The cone of reinforced brickwork which bears aloft the stone lantern and the gilded ball and cross of St. Paul's stands out as conspicuous in the history of construction as the great dome is actually conspicuous above the house-tops. It is still efficient, and has the air of being thoroughly up-to-date in spite of two hundred years of exposure to phenomenal wind-pressures. In respect to endurance, stability, and fine craftsmanship, the best of Wren's building attains such a high level that any falling off in quality in an example of his art seems incomprehensible.

But though we judge him by his own extraordinarily high standard, it would be fairer to recognize that the tradition of building construction had fallen to a low ebb when the great architect began his career.

With the dissolution of the monasteries the Gothic architecture of arch and vault and buttress had been dealt a deadly blow, and throughout the Tudor period sumptuous decoration in colour, carving, leadwork, terra-cotta, and plaster had taken the place of the more vigorous constructional style. In the interval much was forgotten.

The habit of constructing rooms of moderate span, roofed with oak, had allowed many of the carefully-guarded secrets of masonic equipoise to lapse for want of application, and the rules for abutting arch-pressures had been brought down from a living tradition to a stupid and totally inaccurate formula, which is quoted and proved false in one of Wren's tracts on building. Instead of the well-wrought, well-bedded masonry demanded by great arched structures, the more manageable spans and lighter roofs only required a modicum of support, and in some cases the quality of the construction suffered, since comparatively little strength would suffice to meet the lesser needs.

Upon this mediocre practice Inigo Jones had fastened the chains of Palladian architecture, and, versed in the composition of stage scenery for masques and pageants, he never sufficiently emphasized the value of true construction as an element worthy of expression in sound design. Building, relegated to the hidden interior of things and considered unworthy of respect, soon fulfilled expectation and became so, and the inquirer examining behind the stone facings of Wren's cathedral discovers a rubble infilling altogether unrelated to the neat close-jointed large blocks of wrought stone which face the weather and the daylight.

This use of unsquared stone for hearting, core, or infilling, as it is indifferently termed, dates back to remote antiquity, and is either more or less pardonable or pernicious according to the tenacity of mortar and the cleanness and strength of the stone fragments employed in its composition. The practice had persisted all through the Gothic period, and was found by Wren still a normal method of building thick masonry walls; as it still is in the stony districts of Palestine.

The internal core of Wren's eight main piers of St. Paul's

Cathedral has been compared, by different writers, either to Norman or to Gothic infilling, and in some respects it more closely resembles the work of the earlier style.

The proportion of sound wrought outer facing stone to unwrought interior rubble core is of vital importance, and in the large piers and walls of St. Paul's Cathedral the proportion is probably not very high. In the extremely attenuated structural members of a Gothic building there had been little room for core, and wrought masonry had preponderated in piers, arches, and flying buttresses, though rubble infilling had bulked largely in lengths of plain walling.

Wren, born on October 20, 1632, at the rectory of East Knoyle, Wilts, was not born early enough by more than a hundred years to grow with the full current of the arch-building tradition, and had to collect his information on such building matters as best he might. Equipped with immense learning, both in classical archæology and in the science of mathematics, he seems to have resorted to his books, his calculations, and his surveys of Gothic buildings in a state of decay for the solution of each problem as it presented itself in the course of an exceedingly busy professional life. But even the brilliancy of an altogether exceptional mind could not make up for the lack of apprenticeship to a thoroughly sound tradition.

Absolute uniformity of attainment could not be expected from Wren's method of life and study, and his great monumental cathedral reveals the development of the master's ever-increasing power of constructional design as the work proceeded from lower to higher stages.

I

WHAT IS WRONG WITH ST. PAUL'S?

EVER since its first erection St. Paul's Cathedral has been almost continually in the repairer's hands. From time to time appeals are made for large sums of money to place the building in a sound structural state, but after each attempt a further series of defects is brought to notice, and a repetition of the process is found to be a necessity.

The eight main central piers of the building have received a great deal of attention and loom large in the public eye at present. But their weakness is no new discovery, for repairs were begun upon them when, during Wren's lifetime, they settled or shrunk upon themselves and into the foundations in response to the enormous and excessive load they had been made to bear.

The repairs have consisted in every case of patching and replacement of facing stones that have been found to be cracked or burst out from the work, and in some cases the replacements have been of a most curious and futile description. Some of the new stones have been attached to the old with metal cramps, hung on as it were to the weak and defective adjoining core of the interior.

Other patches have been veritably tied on with nails and tow, and could not possibly contribute one iota to the strength of the support. They were frankly inserted in the

interests of neatness, and must rank as "works of art" not as constructional expedients. (Fig. 1.) In fairness to the thoroughness of present-day workmanship it should be at once proclaimed that these wisps of tow are historical. But whether the repairs to the piers be superficial or conscientiously applied, the defects continually reappear in the form of cracks across the stones. Sometimes the cracked stone remains fast embedded in the work, but in other cases frag-

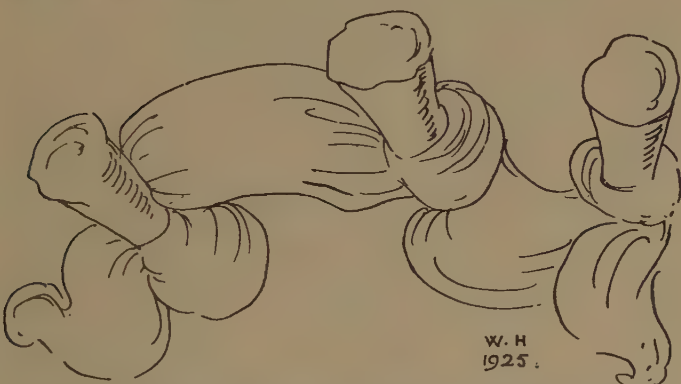

Fig. 1. Some historical patches were tied on to the stonework with wisps of tow and old iron pegs.

ments of their substance "spall" or "flush" off from their faces (Fig. 2), and either fall to the ground or remain precariously perched on some small ledge almost in their original position, perhaps, but incapable of bearing any weight. (Fig. 36.)

Inspection of the interior of the piers through trial holes made during the replacement of defective stones has revealed the fact that the internal rubble core of the piers is also more or less shattered by a series of vertical cracks, and

though earlier builders knew of no method of dealing with these troubles, the modern invention of Portland cement and " grouting "—the insertion of a fluid and watery cement mortar—has been recently experimented with, and is now advocated by the Commission appointed in 1921.

But the defects in the eight main piers are not the only ones to be found throughout the building. The towers at

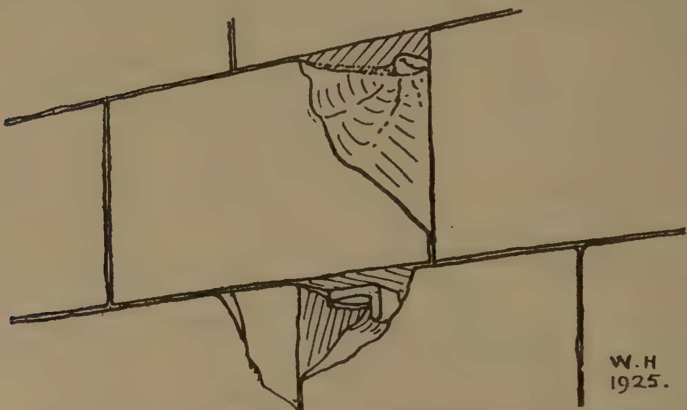

FIG. 2. "Spalling" or "flushing"—the cracking away of parts of the masonry—is caused through excessive or unequal pressures. These may be applied by important movements in the building or by local defects, rusting iron, or imperfect bedding of the stonework.

its west end have sunk on their foundations, and both they and many parts of the enclosing walls have departed from the perpendicular. Generally speaking, the walls lean outward, those on the south and west doing so more markedly than the rest. The dome is also out of perpendicular, but under the circumstances its deviation from the vertical is singularly slight.

In 1921 I had the pleasure of visiting the building with

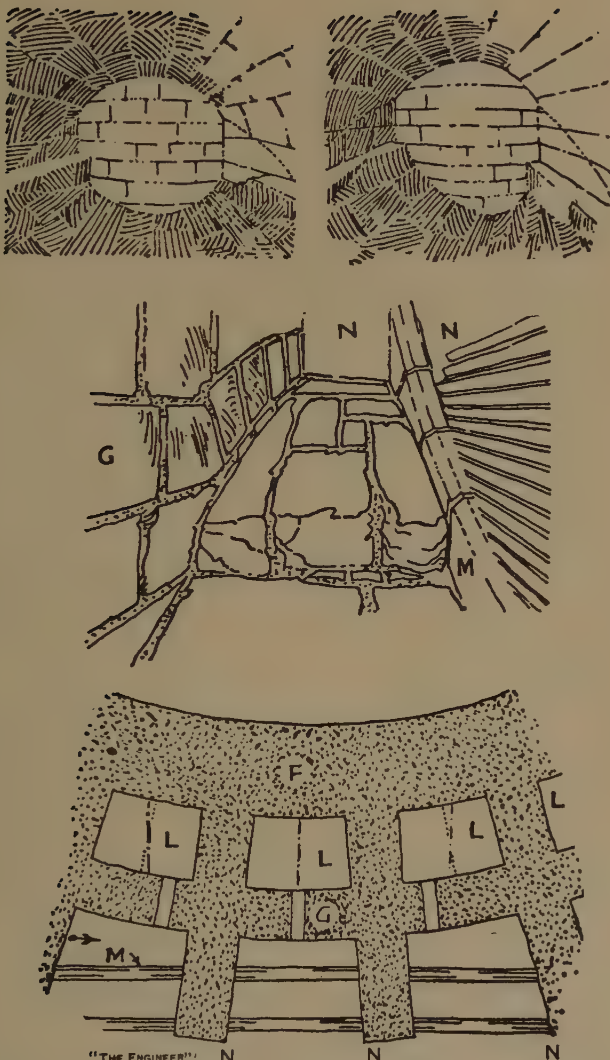

FIG. 3. St. Paul's Cathedral. Plans of counterforts N, cells L, and drums of the dome F and G, also inverted arch rib M. Top figures: Views in two adjoining cells. Middle figure: Upper portion of the great arch spanning nave. Lower figure: Part plan showing three cells. From sketches by the Author.

Mr. Macartney, the surveyor of the fabric, when the centre of the dome was plumbed, and found to be little more than a hand's breadth out of the centre of the church floor. This is an error such as might possibly have been produced in its erection, though the direction of the lean, slight as it is, confirms the known tendency of the building as a whole to bend and lean most freely towards the south-west.

Above the piers cracks have occurred consistently in such parts of the tall central domed construction as might have united the internal and external drums of the dome, and made them act together as a single constructional support.

Some extraordinary instances of fractured stonework (Fig. 3) are to be found in the thirty-two counterforts, or buttress walls which Wren built above the arches and vaults and below the external roofs of the nave, choir, and transepts to spread the weight of the drums with some approach to uniformity upon the backs of the great arches and piers. (Fig. 4.)

At a lower level a consistent series of dislocations and cracks penetrates the masonry of the arches and vaults, walls, window-heads and cills, and encircles the whole group of the eight piers and principal arches separating this part of the building from surrounding piers, walls, and buttresses, and depriving the towering central mass of some part of the protection and support that it should receive from their close contact. (Fig. 5.)

The extremities of the building, too, its gable walls and its projecting corners, show signs of cracking and moving away from adjoining portions and, generally speaking, away from the centre of the building.

As cracks go the cracks in St. Paul's are not particularly conspicuous. Admirable care has been taken of the building,

FIG. 4. St. Paul's Cathedral. Cracks in the counterforts or buttresses of the drum due to the settlement. These have been filled in. Many years ago it was found that the dome had sunk and was severed from the surrounding mass.

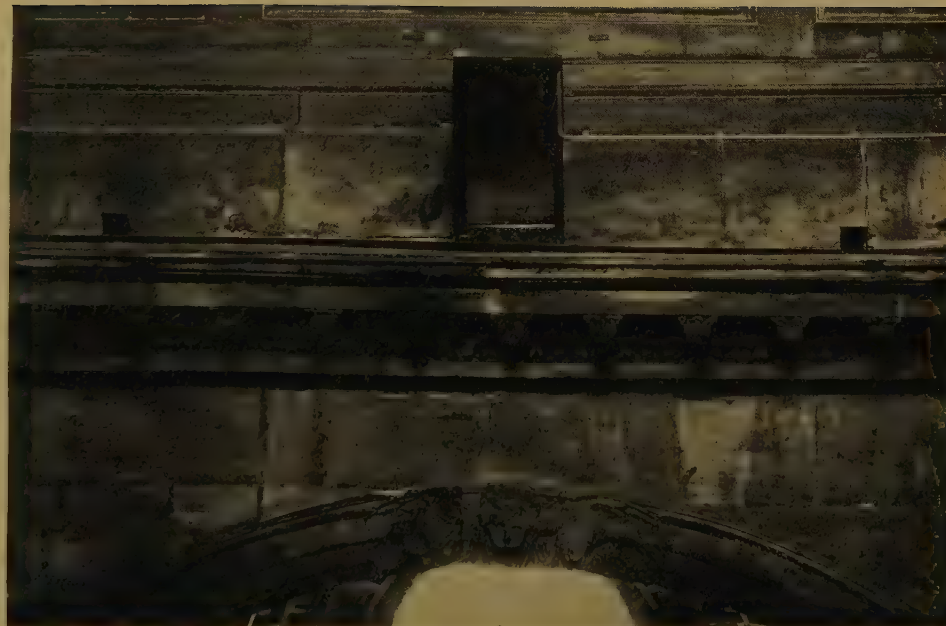

Fig. 5. St. Paul's Cathedral. The cracks and bends in masonry between main dome piers and surrounding walls. The distortion of mouldings is seen by glancing along their length.

and before a crack widens from the thickness of a hair to a gap of an inch or so the defective masonry has been cut out at the orders of a watchful surveyor and a new stone or stones have been inserted. (Fig. 6.)

The question what is wrong with St. Paul's cannot be answered, therefore, by the apparent size of the fractures at any particular moment, and though it is fatally easy to take the size of the crack as the measure of the defect, cracks are in reality but symptoms of defects, deeper hidden in the essential balance of parts and the whole structural circumstances of the building.

A great deal has been made of the fact that St. Paul's Cathedral is a house built upon sand, and not upon rock, and some part of its movements and fractures are probably due to this cause. The thin layer of pot-earth from 4 ft. to 6 ft. thick, which forms a blanket over the water-bearing sand between the foundation and the London clay 25 ft. below, has probably yielded somewhat unequally to the pressure of the great building. (Figs. 7, 30, and 35.) The constant withdrawal of minute quantities of fine sand with the water flowing downhill towards the Thames, or pumped out in baling operations when the basements of buildings or deep-level sewers or railways are constructed in the neighbourhood has been suspected as a contributory cause of subsidence. The withdrawal of the water alone might also be harmful. In addition to these causes wind-pressure and vibration from traffic have been mentioned, though there is a singular silence upon the subject of wind-pressure on the dome in its effect upon the cracking of the eight supporting piers.

What is not generally recognized is that the shape of the Cathedral is largely responsible for the defects and symptoms of decay in its substance.

Every child of the present day may, or at least might, know as a truism, a constructional fact that Wren's great mind discovered only after a life's experience. A building intended to last long must have its shape, its weight, and the strength of all its parts designed in an exact structural relationship to one another.

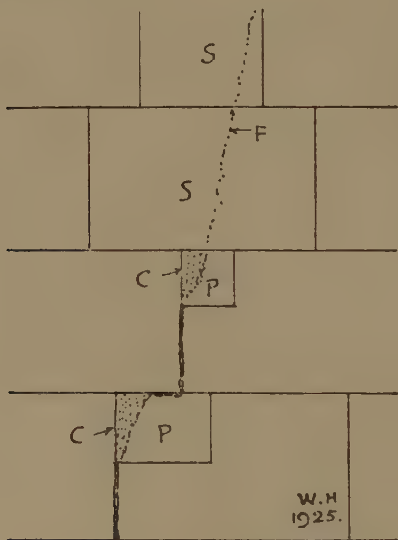

FIG. 6. Patching for neatness and not for strength. Patches P P replace corners C C, and new stones S S cover internal fracture F without removing its cause.

Every element of its construction must be fit for its particular purpose, and calculated to remain fit just as long as all the other elements.

It may then wear out, but it cannot break down. Not Wren's masterpiece only, but every building in which

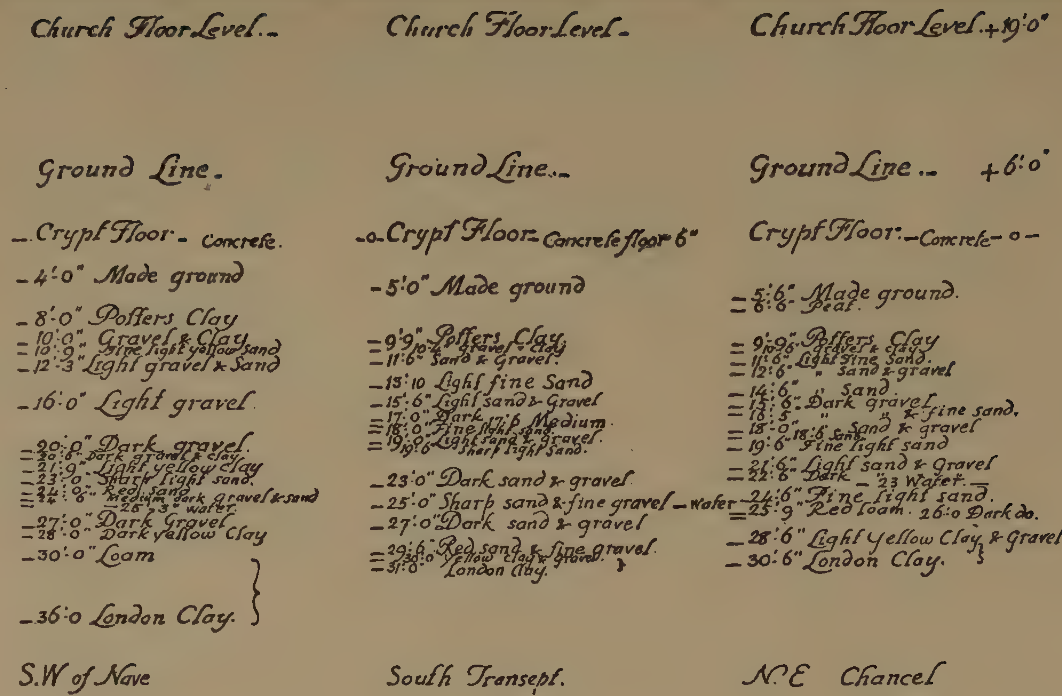
Church Floor Level.
Ground Line.
Crypt Floor. Concrete.
4'0" Made ground
8'0" Potters Clay
10'0" Gravel & Clay
10'9" Fine light yellow sand
12'3" Light gravel & Sand
16'0" Light gravel
20'0" Dark gravel.
20'6" Dark gravel & clay
21'9" Light yellow clay
23'0" Sharp light sand.
24'0" Red sand
24'6" Medium dark gravel & sand
25'3" water.
27'0" Dark Gravel
28'0" Dark yellow Clay
30'0" Loam
36'0 London Clay.
S.W of Nave
Church Floor Level.
Ground Line.
0 Crypt Floor. Concrete floor 6"
5'0" Made ground
9'9" Potters Clay.
10'4" Gravel & clay
11'6" Sand & Gravel.
13'10 Light fine Sand
15'6" Light sand & Gravel
17'0" Dark
17'6 Medium
18'0" Fine light sand
19'0" Light sand & gravel.
19'6 Sharp light sand.
23'0" Dark sand & gravel.
25'0" Sharp sand & fine gravel. water
27'0" Dark sand & gravel
29'6" Red sand & fine gravel.
30'0 Yellow clay & gravel.
31'0" London Clay.
South Transept.
Church Floor Level. +19'0"
Ground Line. +6'0"
Crypt Floor. Concrete. 0
5'6" Made ground.
6'6" Peat.
9'9" Potters Clay
10'6" Gravel & clay
11'6" Light fine sand.
12'6" " sand & gravel
14'6" " Sand
15'6" Dark gravel
18'5" " " & fine sand.
18'0" 18'6 Sand & gravel
19'6" Fine light sand
21'6" Light sand & Gravel
22'6" Dark 23 Water.
24'6" Fine light sand.
25'9" Red loam. 26'0 Dark do.
28'6" Light yellow Clay & Gravel
30'6" London Clay.
N.E Chancel

Fig. 7.

questions of art or of convenience are allowed to modify the requirements of scientific structural arrangement, freely transgresses this rule, and only a few highly exceptional buildings obey it.

The Roman Pantheon, a comparatively simple domed structure more nearly approaches the ideal than other buildings of colossal size, though even it has not the thimble-like curve in contour that would be required for the perfect application of the theory. (Figs. 8 and 9.)

One of the finest examples of a building of this scientific character is Wren's own cone at St. Paul's, which gave to the world the first hint of the definite intentional exploitation of a geometrical shape considered as a unity in three dimensions, and applied to definite constructional functions. In designing this internal cone, which is hidden between the outer and inner domes, Wren had not to worry overmuch about appearance or about the convenience, and the purpose of the building and his inventive genius, directed entirely upon a structural theme, produced a type of building strong in the direct transmission of pressures from summit to base, strong in the compressional support afforded to each of its parts by its rotundity, and strong also in the tenacity of its reinforcing hoops of wrought iron.

Speculative theory, abstract calculation, and accumulated experience must have been required before Wren dared to perch the unusual form aloft over the great central void of his church, and to place upon it the stone lantern that stands, spire fashion, above the whole artistic composition. (Figs. 10 and 10A.)

But before Wren's store of structural knowledge had reached the culminating point at which he could propose to himself the definite control of weights and thrusts with

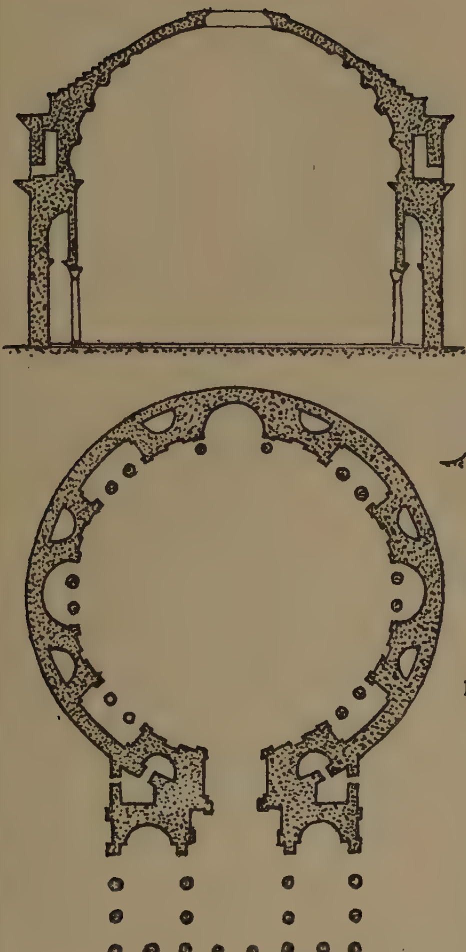

Fig. 9. Plan and section of mud hut.

J.H.H. 1925.

Fig. 8. Plan and section of Roman Pantheon.

The span of the dome, Fig. 8, is 142 ft. 6 ins.

certain foreknowledge of success, he had attempted many experiments in building construction, all of extreme interest, but not all uniformly successful.

In any case it was impossible for him to design the whole building in the shape of a gigantic mud hut, even if he had realized from the outset the constructional principle of apportioning the strength of every stage of the building to the weight that would be superimposed upon it, and of so placing its material as to oppose in the most direct manner possible the combined weights and thrusts of higher parts, and transmit them safely to those below.

The main problem as Wren visualized it under the interfering criticism of the ecclesiastical party at court was to adapt the plan and general disposition of constructional masses of a Gothic cathedral, like the old St. Paul's, to carry the weight and buttress the thrusts of a large central dome, supported upon arches and piers. (Fig. 11.)

The genesis of the design is well known, for Wren had already prepared a plan for building a dome over the central portion of the old cathedral, and the duality of Gothic substructure and Byzantine superstructure becomes apparent upon a careful study of the building in connection with the problems of engineering solved in its erection.

The cross-shaped church consisting of nave, choir, and transepts, all provided with high naves and low aisles, follows Gothic tradition in many of its principal structural arrangements. (Fig. 12.)

It contains the defects of shaping common to Gothic work and some others that arose from Wren's inexperience as a practical builder or from the decay of the Gothic tradition of thrust articulation and management.

The building also suffers from the pedantic shackles of

FIG. 10. St. Paul's Cathedral. An isometric view of the dome, showing arrangement of interior structural devices.

Drawn by William Dunn, F.R.I.B.A., and Matthew J. Dawson, A.R.I.B.A. Traced by W. Godfrey Allen.

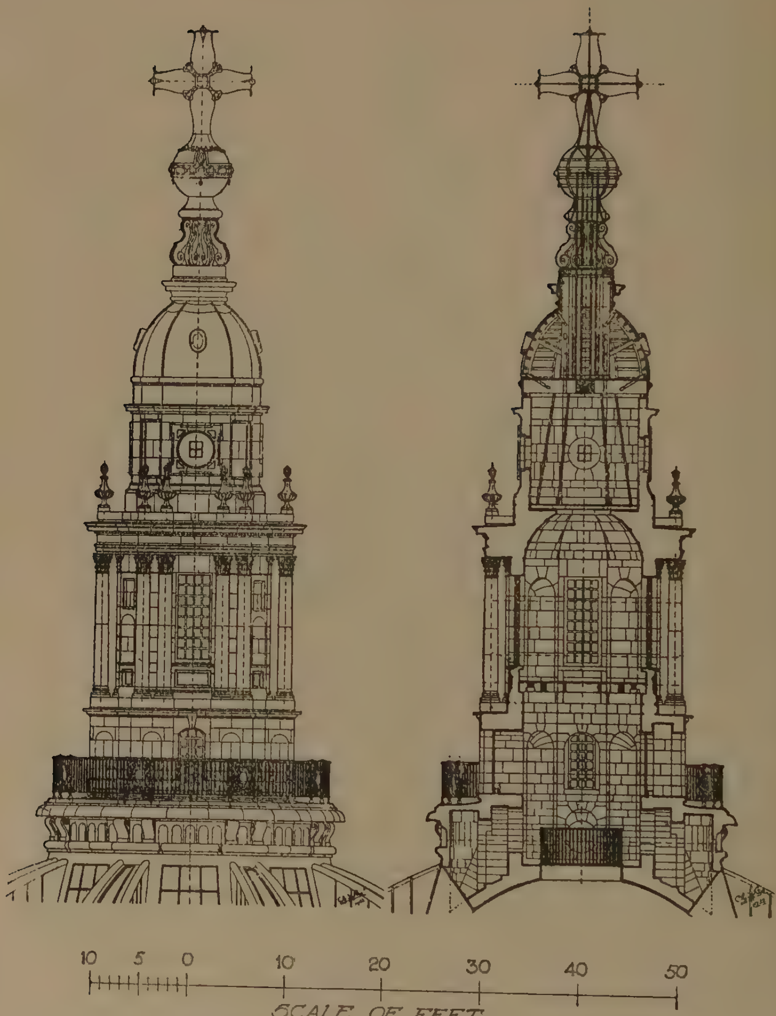

FIG. 10A. St. Paul's Cathedral. Elevation and Section of the Lantern.
Measured and drawn by H. Wright and C. G. Sykes.

the good Roman manner, which insisted upon the use of round-headed arches even where flying buttresses or half arches would have been more consistent with the structural requirements. (Fig. 13.)

A typical Gothic cathedral has little direct reference to the ideal constructional type of the mud hut, which gains strength from its circular form in plan as well as from the correct, though uncalculated, gradation of its sectional contour.

The section of a Gothic cathedral may approach more or

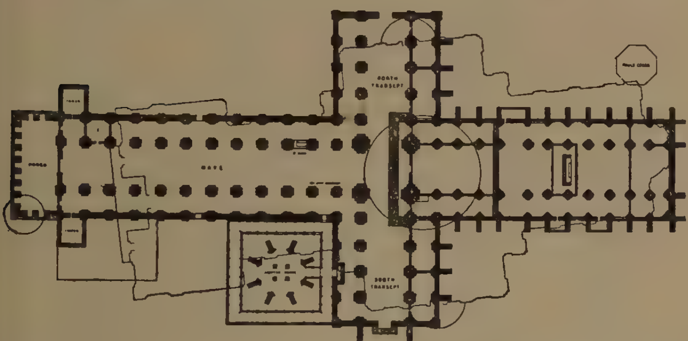

Fig. 11. Ground plan of old St. Paul's, showing in outline the change of axis in the present Cathedral. Wren proposed to remove the four central piers and build a dome over the large central space.

less closely to an appropriate curve of thrust lines in its arrangement of material in high arch, flying buttress, and buttress pier, but the arches and vaults of the aisles push the piers and bend them, about the middle of their height, in towards the central nave. The high vaults, on the contrary, push the upper portions of the piers outwards until the action of the buttress approximately neutralizes their movement. (Fig. 14.)

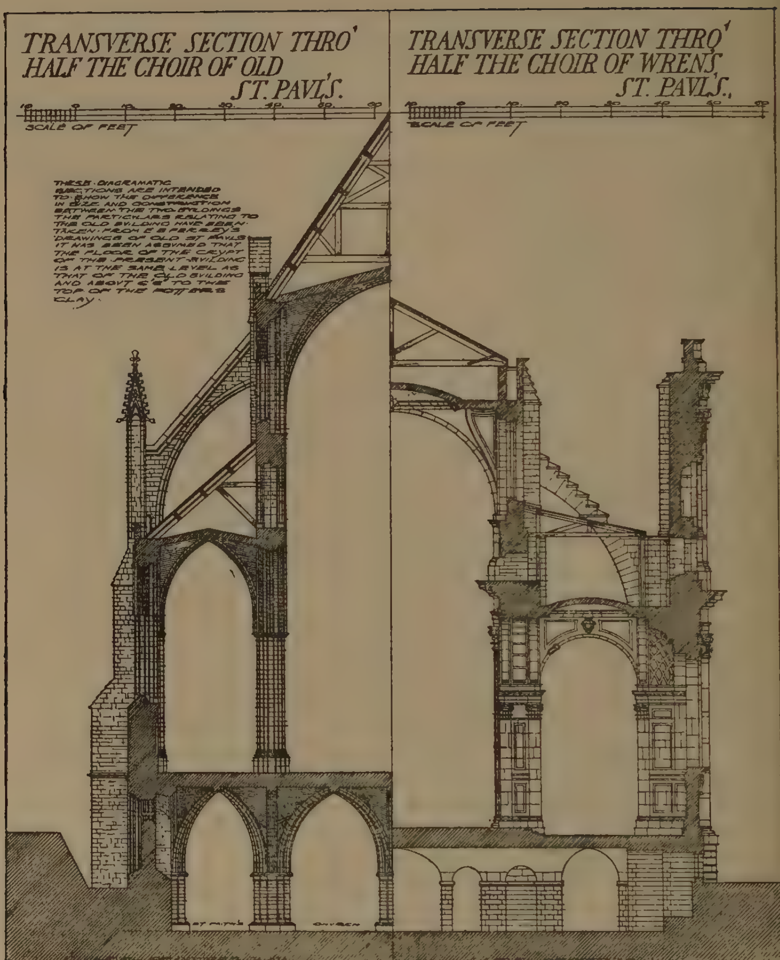

Fig. 12.

Measured and drawn by W. Godfrey Allen.

In some buildings of cathedral type, such as Canterbury and Westminster Abbey, and the buildings erected on the earthquake-shaken shores of the Mediterranean, the aisle arch thrusts are restrained or, rather, modified by metal tie-bars, but even with this provision, the bend on the piers at Westminster can easily be detected with the unaided eye. The four central piers of a Gothic cathedral suffer most since they have to withstand the thrusts of two aisle arches, and are free from lateral support on two sides instead of only one. (Fig. 15.)

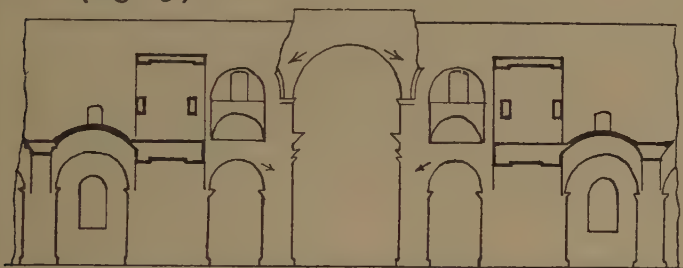

FIG. 13. Round-headed arches intervene between thrusts of the great arches bearing the dome and the masses intended to buttress them. The piers are bending under thrusts of aisle arches and great arches.

The fabric of a Gothic cathedral is also subject to general alteration in shape in the direction of its length. The high arches of the central tower push out upon the upper parts of the clerestory walls, and rack them in the direction of their length, more or less consistently, till the gable-ends of the four arms of the cross-shaped building generally nod outwards at their tops in response to these movements in spite of buttresses provided to resist them. (Fig. 17.)

The behaviour of the lower part of St. Paul's conforms very closely to the action of the typical Gothic cathedral, for, as regards the law of gravitation, the details of the

Renaissance style with which Wren decorated his essentially Gothic building hardly count, or where they count at all do so in an adverse sense. Nature does not care a rap whether a pier is fluted like a group of pilasters, or hung with

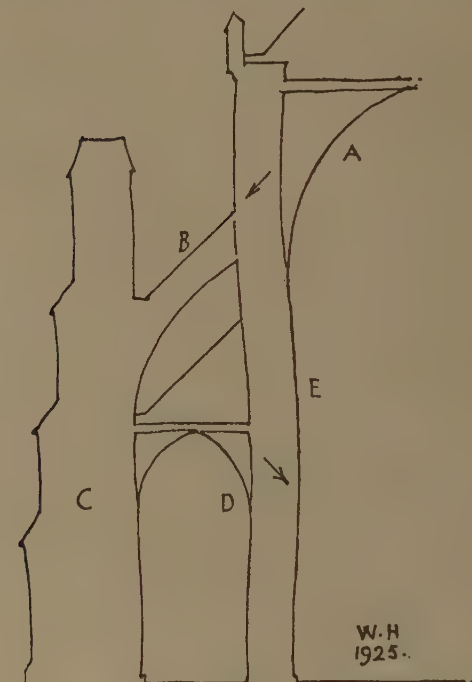

FIG. 14. Bends in Gothic cross section (exaggerated). A, high arch pressing outwards against flying buttress B, and tending to bend it, and its pier C; D, aisle vaults bend pier E in towards the centre of the building. Compare also FIG. 12.

pipe-like ridges, but suitably shaped arches do receive from her more respect than round ones of equal bulk and strength of material.

Fig. 15. Westminster Abbey. An interior view showing the structural deflections in the central piers of the tower. Glance along page from bottom to top to see bends in piers.

FIG. 16. North elevation of old St. Paul's, as shown in Dugdale's "History," 1648. Flying buttresses and pinnacles arranged to direct thrusts downwards.

The provision of eight principal piers to carry the central domed structure instead of four piers supporting a tower has, however, implied a corresponding alteration in the buttress function of the several walls of the church. The aisle walls take thrust in the direction of their length from the arches bearing the central domes as well as taking thrust across their thickness from the aisle and nave vaults. These walls were weighted and stiffened by Wren, who built high blank parapet walls above them to resist the push of the arches. (Fig. 12.)

The arrangement is good, but the mass is not sufficiently great for the purpose, particularly in the transepts, which are of comparatively slight projection and, as has been already mentioned, movements have taken place in the past and are still proceeding. (Fig. 18.)

The lapse of time which had permitted the knowledge of arch and buttress architecture to decay in England drove Wren to make use of experimental buttressing devices of his own invention. The application of lateral thrusts to masses of wall in the direction of their length was nothing new, but Gothic builders had directed the thrusts towards the ground and towards the foundations of the wall as soon as was practically possible. (Fig. 16.)

Wren either did not realize the propriety of so doing, or may have considered that he was justified by some mathematical theory of his own in allowing the lateral thrusts from the main arches under the dome to be applied to the buttressing walls in a nearly horizontal direction. This course is philosophically defensible only when the wall as a whole, or a sufficient part of it, acts as a united mass, and though a wall suitably reinforced for the purpose might so act, a wall of ordinary or of poor construction will not

Fig. 17. Exaggerated sketch showing a Gothic arcaded building in decay. An arcaded building bends in every part before absolutely falling to the ground. The curves occur in response to the adaptation of the material to its conditions of shaping and loading, but have been mistaken for purposeful artistic refinements by some observers.

Fig. 18. Section through transept of St. Paul's on line of great pier. The buttressing action of the face wall A of the transept is very slight and is showing signs of failure.

Fig. 19. Temple Bar. Showing Wren's use of horizontal abutments to arch pressures. Compare with Gothic flying buttress form of arch and pinnacles on Fig. 16.

continue to do so indefinitely. Time enters into the question, for every slight displacement of stonework in the courses of the wall permits of a corresponding movement in the arch. The arch follows up every infinitesimal gain of ground obtained by the agencies of vibration and decay, which aid its thrusts in their long continued action. (Figs. 19 and 20.)

How far movements in the buttress masses of St. Paul's Cathedral are affecting the condition of the eight main piers

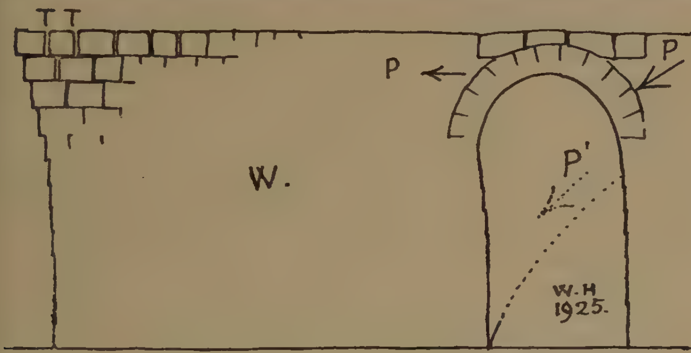

FIG. 20. Temperature cracks TT aid pressures P applied in a horizontal direction and tend to dislocate the material of the buttress. Pressures P′ conducted downward under the weight W in the Gothic manner are not so dangerous.

of the dome must ultimately be ascertained in minute detail before a rational scheme for their repair can be designed. That the inquiry has not already been systematically put in hand is due partly to the cost and labour involved in such researches, but principally because, in this age of steel stanchions and girders, no person in authority feels competent to undertake it or pursue it to a useful conclusion. And, to be useful indeed, the inquiry would have to be undertaken by some surveyor familiar with work of this nature.

While it is possible to recognize that the piers are most

certainly adversely affected by the movements in the arches they support and in the buttress masses which are absolutely necessary to maintain them in a vertical position, it is not yet possible to give accurate figures for the stresses involved.

In the meantime the piers are splitting under the excessive weight as well as bending under the pressures applied to them by the arches.

In response to the load of the domed central mass the eight piers are found to have sunk from $2\frac{5}{16}$ in. to $6\frac{1}{8}$ in. farther than the rest of the church when measured at the level of the main cornice.

This does not mean that they have descended bodily into the ground, but that, having pressed into the ground to a somewhat greater degree than the surrounding lightly-loaded parts of the Cathedral, they have also had their stonework and mortar joints squeezed together into a smaller space.

What is much more productive of cracks in their substance is the unequal application of the load to the top of each pier. The Whispering Gallery and the great inner drum stand out several feet over the internal space between the piers, and their enormous weight is conducted by means of the pendentives and by the great arches on to a small portion only of the pier at its inner corner. (Fig. 21.)

The danger is that this inner corner, marked A in Figs. 22 and 27, will split away and fail, kicked out of position by the diagonal arches across the corners of the octagon.

These arches press out more and more dangerously as they come to receive a greater and greater share of the load with the partial, but steadily increasing failure of the 32 counterforts, the semi-domes and the buttressing action of the bastions.

A complete structural analysis of the building would take

a surveyor and several capable assistants many months, and would involve the making and testing to cracking point of models carefully made to scale to represent the main masses of the building; but, in default of such exhaustive and costly

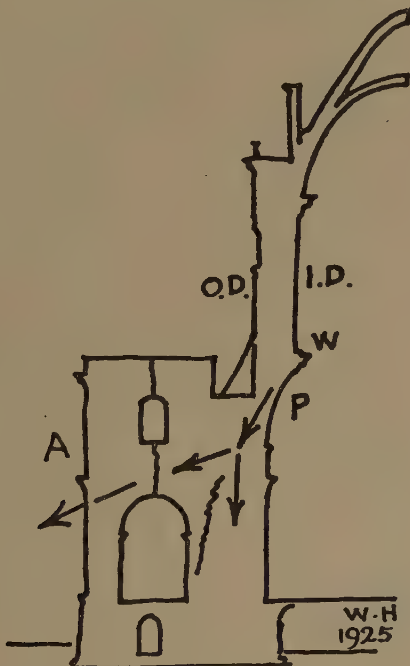

Fig. 21. Inner drum I.D. and Whispering Gallery W, at St. Paul's, stand out over the void, and their weight is conducted on to a small portion of the pier top by pendentive P. The load reaches the pier, not only in concentrated form, but with a dangerous overturning tendency which is only partly restrained by the buttress action of transept A.

measures, a more generalized impression of the facts can be obtained from observation of the building and by testing models made of plastic material. When such models are

loaded with a weight upon the circle of the inner drum it is recognized that the defects in Wren's work are primarily due to the nature of its design, to the imperfect co-relation of its shape, its weight, and the strength of its material.

The boldness of Wren's scheme for piling an enormous domed structure within a cathedral essentially Gothic in its proportions is really to blame for the periodical demands for repairs. The whole building is light and delicate in the extreme, when considered in regard to the diameter of the dome and the height of the central towering masses.

It appears particularly fragile when compared with St. Peter's at Rome, for Wren's eight main piers are long and narrow, and allow of uninterrupted aisles from west to east, and north to south, while the piers at St. Peter's are gigantic L-shaped blocks, capable, or almost capable, of resisting the thrust of the main arches and pendentives of the dome without further assistance of any other buttressing masses. (Figs. 23 and 24.)

Wren's domes are comparatively sound, and his substructures weak; St. Peter's substructures are fairly sound, thanks to the fact that they were repaired after having been found imperfect by Michael Angelo, but the dome is weak, although supplied with iron bands at different times after its erection. (Figs. 25 and 26.)

A comparison of St. Paul's and St. Peter's brings out the intense dissimilarity of the two buildings, for Wren's eight long and slender piers would scatter, fall apart, and fly to pieces in a moment if entirely deprived of the buttressing effect of the bastions and the walls and arches of the adjoining parts of the church.

Although the Commission that has been investigating the structure for the past three and a half years seems to regard

Fig. 22. Exaggerated view of bends and cracks such as might be expected to develop in piers loaded like the eight main piers of St. Paul's dome. A = corner of pier overturning into high nave. B = corner overturning away from centre of dome. The danger of corner A failing as a separate mass is very grave. These twists and bends of the piers are not even mentioned in the Commission's Final Report, and are ignored in its optimistic estimate of the building's stability.

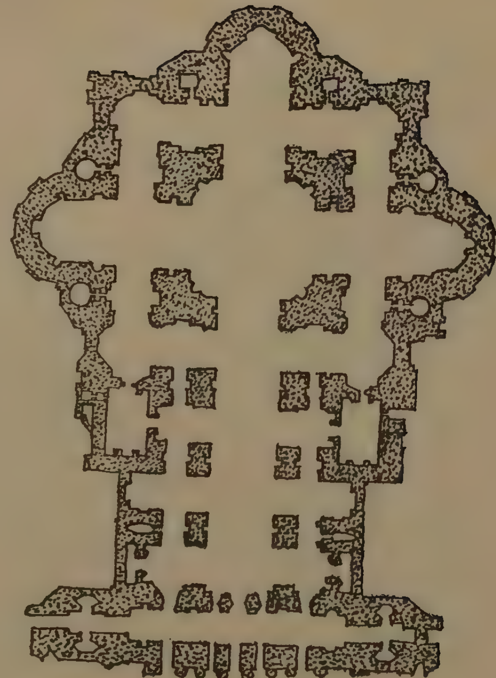

FIG. 23. St. Peter's, Rome.

FIG. 24. St. Paul's, London.

The plan of one great dome pier at St. Peter's could almost cover two of Wren's piers at St. Paul's together with the corner bastion and the intervening aisles.

Diameter of St. Peter's dome 137 ft. 6 ins. Diameter of St. Paul's dome 109 ft.

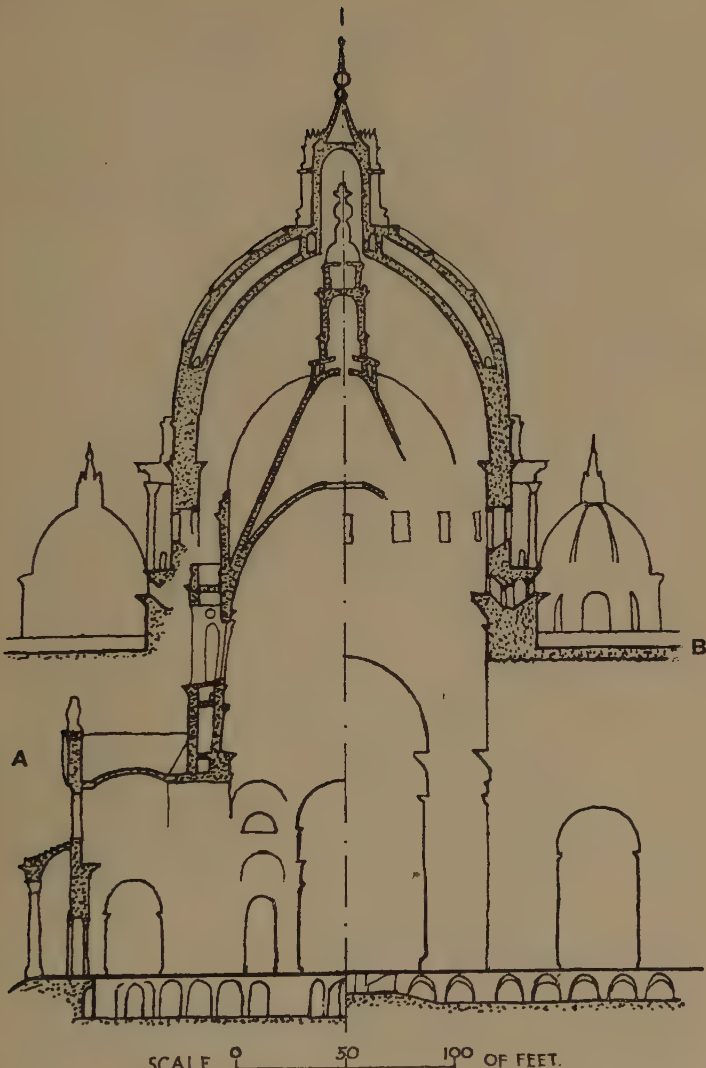

FIG. 25. Section through transepts, St. Paul's Cathedral.

FIG. 26. Section through dome, St. Peter's, Rome.

The height of Wren's domed central mass above the level of the crown of the main vaults A is practically equal to that of the domed mass of St. Peter's above its main vault B.

the defects in the piers as a simple question of excessive weight and feeble material, the movements in these buttressing masses must be restrained or money and labour spent upon the repair of the piers as separate works will merely be thrown away, however sound the new workmanship and however solid the new masonry. To the characteristic defects produced by the action of the loading upon the shapes and the materials of the building, all other destructive agencies contribute their separate damaging effects.

Thus, while wind-pressure has not shown itself capable of overturning the dome, nor movements in the subsoil of making it lean more than half a dozen inches in the course of two centuries, their effects are not, therefore, negligible.

Granted, as it must be granted, that the piers are bending and twisting under the arch pressures set free by the slight movements in the surrounding buttressing masses, and that they are being split into separate portions by the eccentrically applied weight, the effect of wind-pressure, of temperature changes, of vibration, and of movement in the subsoil is to supply a rocking and grinding action which gives a further destructive force to the loads and pressures. The effect upon the pier is that of a crowbar in process of being driven down into a heap of stones. The downward impulse is constant, but the displacement of material to one side or the other as the bar is ground round and shaken provides fresh opportunities for the continued descent of the iron point.

To apply this simile to the great building, the pointed lower extremities of the pendentives under the whispering gallery may be regarded as the sharpened points of giant crowbars pressed with great and steady force upon the shattered substance of the piers. To this steady destructive force vibration, due to wind-pressure and the impact of gusts

FIG. 27. The eight main piers of St. Paul's Cathedral are being twisted, bent, and overturned as well as crushed by the excessive load. They are splitting in response to highly complex cross-thrusts, some of which are becoming more dangerous with the partial, but increasing, failure of the buttressing system. The piers bulge inwards at A in response to the kick and settlement of the diagonal great arches which receive more and more load as the bastions receive less and less through decay in the semi-domes and counterforts.

upon the exposed surface of the dome, adds intensity and a constantly varying direction. Movements due to temperature changes and vibrations from the ground have a somewhat similar effect in that they present the material in different conditions to the steadily applied weight. (Fig. 27.)

The piers having divided by fractures into several portions under the loading conditions reacting upon the shape and material of the building, the fractures are opening more and more completely under these rockings of their load. That cement grout should unify for any long time masses thus continually sundered afresh is not a probable contingency, and it is high time that the force of each giant crowbar should be reduced and its rocking action restrained by means of properly calculated reinforcement scientifically applied to the building.

II

CONSIDERATIONS OF DETAIL

TO the various committees and commissions that have advised upon the condition of St. Paul's Cathedral the problems of its repair have presented themselves singly and in detail.

At one time the question of safeguarding the outward leaning west front with its segmental vaults spreading, cracking, and subsiding in length, as well as breadth, was placed forcibly before the public. (Fig. 28.) On another occasion the south-west tower with its tendency to sink, overturn, and part company with the rest of the building has been the matter selected for discussion. (Fig. 29.)

At a still later date the foundation of the Cathedral upon its layer of potters' clay became a matter of special anxiety in connection with proposed tunnels in the neighbourhood. (Fig. 30.) And now the comparatively recent discovery of defective rubble core in the heart of the eight main piers of the dome has centred all interest on the question of the danger or the safety of the high domed portion of the building.

The second interim report of the Commission appointed in 1921 is practically confined to the discussion of these piers, and a proposed method of strengthening them with cement grout.

THE SECOND INTERIM REPORT

The report, which is dated December 29, 1924, is in the following terms:—

The Dean and Chapter of St. Paul's.

St. Paul's Cathedral.

The Commission's Second Interim Report.

Gentlemen,—At a meeting at St. Paul's on Friday, December 5, it was decided that a second interim report should be made, giving the result of the further examination which has been made by your Commission since their report of June 1, 1922. In that report your Commission referred to the condition of the masonry of the main piers, and the consideration of your Commission has for some time been largely concentrated on the best methods of consolidating the interior structure of the main piers, which carry a considerable proportion of the great load of the drums, the inner and outer domes, and the interior cone, which strengthens the outer dome itself and also carries the external lantern and cross above.

Various experiments have been made with the object of strengthening the interior rubble filling of these piers by injecting cement under pressure into the cavities that exist in the rubble filling. This has presented special difficulties owing to the character of the filling.

Your Commission have decided to recommend the adoption of the plan which has been experimentally used on the north-east pier, and with which they are satisfied, for, although it is practically impossible to say that the whole interior of the pier has been completely consolidated, they are of opinion, after examination, that sufficient has been done to strengthen it satisfactorily, such treatment to be followed by a gradual replacement of the broken external

FIG. 28. St. Paul's Cathedral. Drooping and fractured masonry at the west end.

FIG. 29. The South-West Tower of St. Paul's.
Years ago the tower was reported out of perpendicular, but this fact was not associated with the general drift of the arches and buttresses throughout the building towards a point of weakness. See also figs. 17, 18, 55, 64, 65, and 70.

facing stones as already carried out by the surveyor of the fabric, Mr. Macartney, on the south-west pier. If this treatment is adopted, your Commission believe a new lease

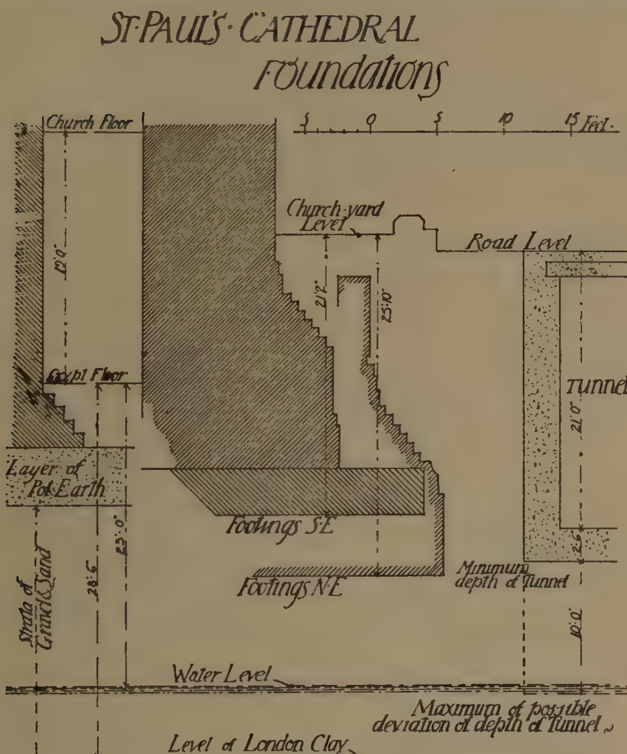

Fig. 30.

of life will be given to the piers at a reasonable expenditure of both time and money and without serious disturbance to the services.

The question of approximate cost is not easy to estimate,

but, taking the actual cost of grouting and cementing part of the north-east pier, and the actual cost of repairing the stonework of the south-west pier by Mr. Macartney, the cost may be put at from £120,000 to £140,000.

Your Commission have also discussed the alternative of reconstructing the piers entirely, and, while they do not doubt the possibility of doing this, though it might involve the taking down of the dome and its supports, yet, in view of the enormous cost and the necessity of closing the greater part of the Cathedral for several years—to say nothing of the great risk or disturbance involved—your Commission are convinced that the wiser course would be to grout and to repair the piers in the first instance, as above indicated, leaving it to a later generation to undertake the larger operation should it at any time become absolutely necessary.

Your Commission, therefore, recommends that the grouting of the piers on a carefully prepared programme, together with the repairs to the stonework, should be proceeded with. They wish to record their opinion that this should be done forthwith. It will naturally take time to carry out, but unless put in hand at once and vigorously pressed to a conclusion, they consider that the situation may rapidly become grave.

We are, gentlemen,
Yours faithfully,

ASTON WEBB. G. W. HUMPHREYS.
E. C. TRENCH. MERVYN MACARTNEY.
BASIL MOTT.

After the issue of this report, with its ominous threat of danger ahead and its lamentable neglect to outline any adequate scheme for putting the building upon a sound

structural basis, a protest became necessary, and the two following chapters are intended to point out that there exists in England a tradition of repair work on the principle of complete conservation which should most certainly be applied to the case of this most majestic building.

The chapters are written to advocate a course of scientific study of the building and its application to the problems of conservation rather than to insist that any specific means should be adopted.

The idea of wrapping a cone around the thirty-two defective counterforts is put forward as one method of dealing with the problem of repairing them, and of steadying and partially supporting the dome during the difficult period when repairs to the piers are in progress, and when it will be intensely desirable to minimize, as far as is humanly possible, the hazardous nature of the work.

A conservator working in the light of the traditions created in England in the repair of historical buildings would not wish to confine himself to one single suggestion of this nature, but would design alternative schemes during the period of examination and analysis of the building and guide himself in the final selection by the considerations of maximum efficiency and minimum interference with the appearance of the ancient work.

During the preparation of this book several other proposals have been made by engineers, but the majority of them are characterized by the drastic nature of the means and appliances to be adopted.

Deep pits are to be sunk in the middle of the building, which is to be lifted up and lowered again by rams of unheard of power quite irrespective of the possibility that the shattered masonry might be altogether destroyed in the process.

DAINTINESS OF HANDLING

As contrasted with these violent measures, the methods of conservation are not dramatic; they do not make their appeal as the "Work of Giants," or "Another Labour of Hercules." Daintiness of handling is, above all things, necessary in dealing with a building which is nearing the point of collapse, the means of support must be strong and dependable, but their application should be judicious rather than vehement.

III

CONTRASTED METHODS OF REPAIR

THE preservation of St. Paul's Cathedral is a matter of world-wide importance, and a means of restoring it to a sound structural condition must be found.

At the moment, such a scheme as will synthetically supply the deficiencies of Wren's wonderful building has not been laid before the public, and in its place are two rival proposals, each of which fails essentially to do justice to one side or the other of this complex problem.

The dangerous-structure notice served by the surveyor of the City Corporation upon the Dean and Chapter of St. Paul's Cathedral comes as a natural corollary to the partial proposals hesitatingly put forward by the Commission appointed in 1921 to investigate the condition of the structure. The recommendation of the Commission to repair the shattered and yielding piers with cement grout and by the piecemeal replacement of damaged stones with new is capped by the suggestion that the dome and its supporting piers be demolished forthwith. It would be difficult to determine upon two alternative proposals more repugnant to the principles and practices of sound conservation as understood in this country by professed lovers of ancient and historical buildings.

Stated in their simplest terms, these principles are to

conserve all original work and to introduce only such alterations and additions of new material as will be required to fulfil the conditions of permanent stability and safety.

In practice some concessions may have to be made in the face of overwhelming physical difficulties opposed to the carrying-out of these principles in their ideal completeness, but the prospect of the possibility that one point or another may have to be conceded on compulsion is no argument for abandoning the whole position without a struggle.

Ultimately, rebuilding will be required, as the Commission itself indicates, even if the proposal to patch the piers is put in hand, and the admission is enough in itself to condemn the obnoxious and ill-conceived scheme.

It should not be considered permissible to entertain for a moment the thought of either demolishing the dome or of allowing it to decay towards its fall for lack of intelligent treatment courageously applied.

Wren's veritable inventions in building construction have a value as landmarks in the history of structural science that would be absent from any imitative reconstruction, however sound, and though the present Commission confesses in its report its lack of will or lack of power to preserve the important historic objects, it would be both stupid and incorrect to suppose that the world holds no architect capable of taking a sounder view of the problem and of turning legitimate aspirations into accomplished facts.

The feebleness of the proposals contained in the Commission's report is the more incomprehensible in that England is possessed of a public office endowed with an

admirable tradition in respect to the examination and structural analysis of ruinous buildings, and their repair by scientifically-applied consolidation and reinforcement.

St. Paul's dome, condemned as a dangerous structure, may be fittingly examined in the light of experience gained in the study of other partially-ruined buildings containing imperfectly-buttressed arch and vault thrusts and heavy and eccentric loads.

The behaviour of ancient vaulted buildings falling into decay is in some particulars constant, and the habitual examination of many examples is a necessary preliminary to the acquirement of facility in diagnosing correctly the causes of defects in any building newly brought under observation.

Whether the Commission does or does not possess the experience that would enable it to grasp the meaning of the defects it examines must interest all who care in the slightest degree for the safety of St. Paul's Cathedral, either as a sublime work of architecture, or as a mass of material dangerously poised aloft.

The question may admit of an affirmative answer as regards individual members of the Commission, but evidence in support of such an answer would be looked for in vain in their recently-issued second interim report.

Under the conditions of loading to which the supporting piers of the dome are subjected the proposal to repair their external stonework facings by piecemeal replacement is fundamentally inadequate and unsound.

Under the terrific and unequally applied pressures that are causing the defects in the building, each stone in the neighbourhood of the principal fractures is in the nature of a potential sacrifice to the inexorable laws of gravitation.

A new stone is stronger than an old one, no doubt, but, unless the resistance of the supporting piers can be increased in very much more adequate measure than can reasonably be hoped for by the grouting scheme, the introduction of a new stone is attended with the grave present risk that an adjoining old stone will be fractured in turn. In the course of months and years this risk of cracks extending is not merely a risk, but a certainty; a certainty which the Commission seems dimly to foresee in its reference to "a later generation," but which it is not prepared to face with the necessary courage at the present time. The danger of new patches in old garments is familiar as a household proverb all the world over, and former repairs at St. Paul's Cathedral are practical demonstrations of the near relationship between the theory and the facts.

Wren's work at St. Paul's is not all of equal value, either in design or execution, for between the commencement and the completion of the building a whole new world of scientific invention as applied to structure was discovered by Wren himself as his experience accumulated, and as his attention was directed to one new problem after another.

The inner dome, the cone, and the lantern of St. Paul's Cathedral embody the result of mature knowledge and discretion, a profound insight into the nature of structural stresses, and of the expedients proper to deal with them. Lower parts of the building, designed and put in hand before Wren's exceptional powers of inquiry had been directed to all aspects of building construction, continue the decadent Gothic traditions of structural material and method which were still in force and which, but for his personal love of experimental science, might well be in force to-day.

Looking at the problems of repair at St. Paul's Cathedral

with a knowledge of the expedients that Wren himself devised in its upper parts, and from the point of view of the new science of conservation that has been created within the last decade, it is possible to claim that modern British architecture is in possession of powers amply sufficient for their solution. But these powers are still potential powers not yet gathered together in the person of a single individual architect, nor yet directed to the case of St. Paul's Cathedral with its peculiar difficulties due to its exceptional dimensions and the materials of which it is composed.

Rejecting as insufficient the proposal to patch the supporting piers, and protesting against the suggested demolition of the dome as an altogether outrageous breach of trust, it is necessary to determine what alternative measures are practicable, and for this a comprehensive examination of the structure is necessary.

Much information would have to be obtained and digested before a scheme could be evolved in all its details, but before descending to detail it is possible to review the most obvious structural movements of the building, and by comparison of these movements with recorded defects in other buildings to determine whether St. Paul's Cathedral must be regarded as altogether exceptional or whether its defects are indeed the ordinary results of ascertainable causes. Vibration produced by traffic and the undermining and draining of the subsoil in building operations near the Cathedral were formerly considered as primary causes of the cracks that have developed and are developing in its masonry, but though these elements are important they are now recognizable as only contributory to the defects which are accounted for by the imperfect statical equipoise of the building and the comparatively weak material of its construction.

The ground plan (Figs. 24 and 31) shows an arrangement of piers and masonry masses disposed around the central point of the church in a fashion admirably adapted to receive the weight of the high and heavy erection of drum, domes, cone, and lantern, piled up above them, and even to act as buttresses to the lateral thrusts of the arches and of wind-pressures to which the outer dome is exposed.

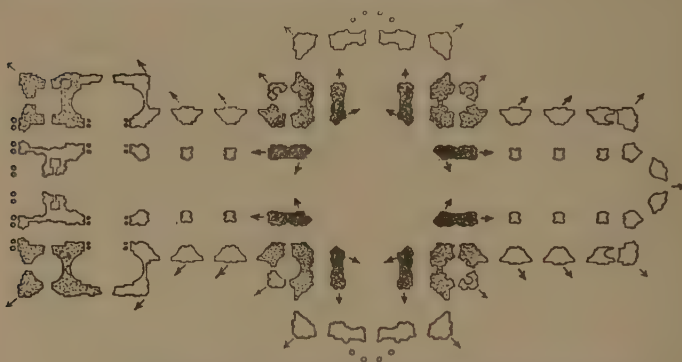

FIG. 31. Diagrammatic ground plan of St. Paul's. The masses of masonry surrounding the eight piers of the dome should afford them support, but adequate means of distributing the weight upon them are lacking at present. Such means might be supplied in a comprehensive scheme of repair. Intense pressures are indicated in black. General tendency of supports to overhang is shown by arrows. The overhang is not absolutely uniform, but the heavily loaded portions of the central piers tend to tear free from the surrounding work.

Four masses of building projecting bastion-wise at the re-entrant angles of the transepts and aisle walls seem to promise security in resisting loads and in their capacity for buttress action, though in this they show signs of failure.

The section of the building shows, however, that the full strength of these masses of material is not adequately employed, and while some of them are subjected to enormous

concentrated eccentric pressures, others are comparatively lightly burdened. (Figs. 32 and 33.)

Wren very seriously under-estimated the importance of diffusing the pressures upon the supports throughout the lower parts of the work, and in consequence even such provision as he made for the diffusion of pressures has been rendered still less effective by the movements in the structure during and since its erection. It is an invariable rule in heavily-loaded masonry that fractures tend to occur between heavily-loaded and lightly-loaded portions of the support, and at St. Paul's the symmetrical disposition of the cracks approaches very nearly to uniformity consistently with this rule. (See Fig. 4.) The daring nature of Wren's design, with its enormous central load, is well illustrated in Figs. 23, 24, 25, 26, and 34.

The arches bridging the spaces between the main piers of the dome and the surrounding walls are all severely dislocated, for the dome piers have compressed bodily to a much greater degree than the lightly-loaded exterior masses. (Figs. 37 and 47.) The arches, semicircular or elliptical, were not designed to transmit thrusts satisfactorily as flying buttresses. In addition to being heavily loaded in comparison with other parts of the building, the eight dome piers are so placed in regard to the position of the inner drum, the pendentives, and the great arches of the dome that they receive their weight as a concentrated eccentric load upon a small portion of their area. (Fig. 40.) The eccentricity is so severe as to have occasioned a series of fissures between the heavily-loaded and lightly-loaded portions in the substance of the piers themselves. The fissures which penetrate the substance of the rubble core of the piers, as well as its wrought stone facing, have given rise to anxiety as to the safety of the building. Fractures in the masonry appear in Fig. 36,

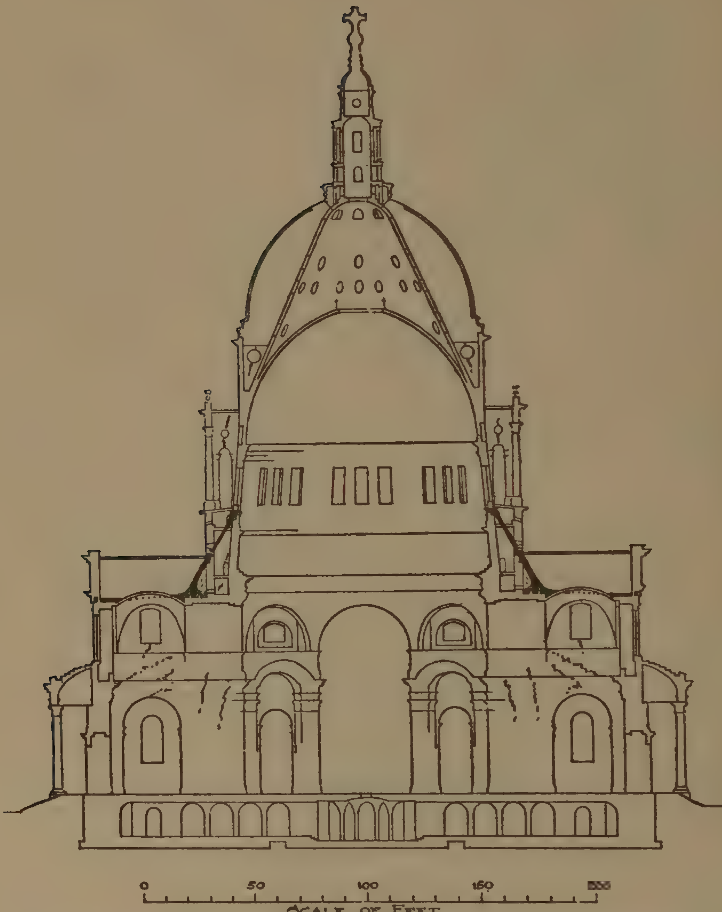

FIG. 32. St. Paul's Cathedral. A.—Cross-section showing positions of principal defects and suggested cone to diffuse the weight of the drum over the tops of piers now being crushed by eccentric loading on one inner corner of each. The cone, or some such device, would be required to hold the upper portion of the building steady during the execution of principal repairs below—the re-coring of the piers with reinforced concrete.

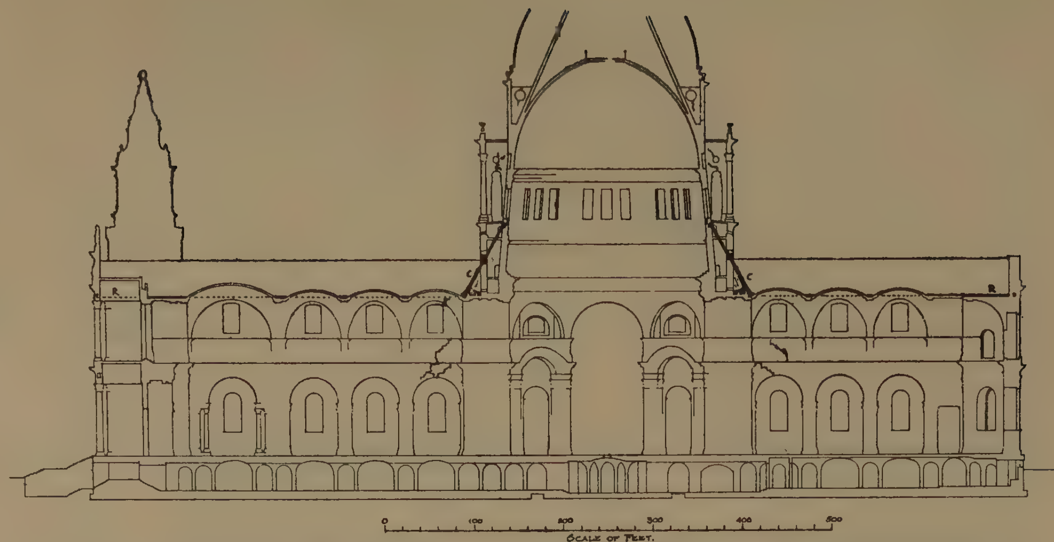

FIG. 33. Long Section, St. Paul's Cathedral. Ragged lines show the positions of some principal dislocations of masonry. C=proposed cone, R=reinforced bands of concrete. The re-coring of the main piers cannot be indicated, but would be put in hand from the foundations right up to the bearing of the drums upon the great arches.

and the nature of the material in the piers is indicated in Fig. 38.

That cracks have opened principally in response to inequalities of pressure and consequent inequalities in contraction in the masonry is confirmed by the behaviour of other parts of the building subjected to similar damaging conditions. At the level of the Whispering Gallery the inner and outer drums are surrounded by a series of thirty-two buttresses, which have all been shattered by the stresses produced by the inequality of pressure upon their inner ends, which are descending with the heavily-loaded drums, and their outer ends which are held up by the tops of the less heavily-burdened portions of the arches, barrel vaults, and semi-domes connecting the eight main piers. A series of fractures throughout the higher parts of the building tends to isolate the heavily-loaded inner drum from the lightly-loaded outer drum and colonnade (Fig. 39), and the cone from the upper drum of masonry surrounding its base.

While these conditions of loading remain as they are at present an attempt to deal with defects in the piers by grouting and patching can only be in the nature of a temporary palliation of symptoms and not a cure of the disease. The statement that the two piers already treated have been examined, and that the treatment has been found successful, can only be accepted as relative and conditional, for it is only a question of time before the essential trouble commences once more to reveal its presence in the former manner. An impartial search, diligently conducted, would certainly reveal traces of movement in or near recently-executed repairs to the stonework.

Another general cause of movements and of fractures throughout the building is to be found in the thrusts of the

Fig. 34. This view of St. Paul's is interesting as showing how the drum bearing the great dome is in turn supported on its eight piers. The view also reveals the true walls of the nave, transepts, and chancel behind the screen walls which alone are seen from the street.

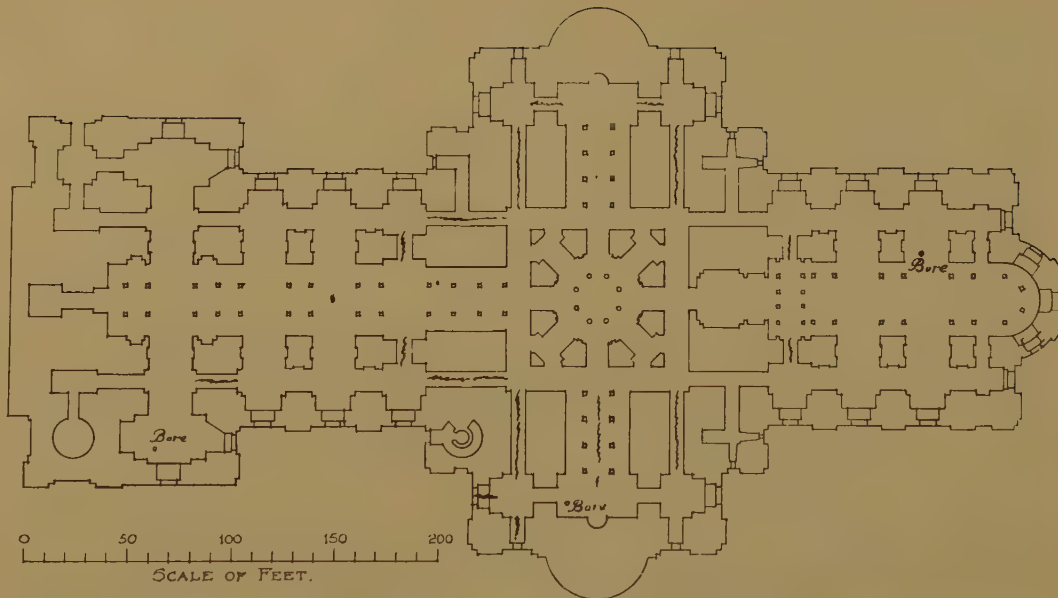

FIG. 35. Crypt plan of St. Paul's Cathedral. Large masses of masonry provided in piers, but weights unevenly distributed upon them.

vaults, which have tended to overturn the outer walls away from the centre of the building, and have contributed to the formation and widening of cracks between the eight central piers and the other parts of the fabric.

A diagrammatic statement of these principal tendencies is shown on Fig. 31, where the arrows indicate the general movements of the building. The black patches indicate the positions of the most concentrated pressures. It should be noticed that the main piers overhang inwards under the combined effect of the heavy eccentric loads on their inner ends and of the thrusts of the aisle vaults and the diagonal great arches. As well as the fractures and disintegration in the main piers, which must be considered as principal defects, subordinate movements of the towers and walls require control, and in a complete scheme of repair it might be practicable to improve the condition of several portions of the building by dealing with them as parts of a whole which, disunited at present, must be brought to a united condition.

The considerations which would be kept in view in devising such a scheme would be: (1) conservation of the maximum amount of original work compatible with safety; (2) the avoidance of new material where it would encroach unpleasantly to the detriment of the artistic amenities of the building; (3) to remedy the structural condition of each defective part in such a manner as will best serve to unite the whole.

The fundamental difference between such a scheme and the proposal to mend by patching is that mending by patching can only remove the outward signs of decay, and the structural improvement attainable by this means is at the best confined to increasing the resistance of the material in the parts actually patched. The more comprehensive

scheme aims at adjusting the pressures and the whole statical condition of the damaged building in conjunction with the repair of specific defects in detail.

Resistance of the material is improved, and at the same time the most excessive stresses are reduced by the suitable application of the remedial measures. The cost of patching may be less at a given moment, but where there is no adequate safeguard against the continued developments of defects, and the need of further patching, or of "larger operations," is certain in the near future, the financial outlook is not really favourable to the patching system.

The increased cost of a comprehensive scheme pays for itself in the course of years by reduction in maintenance charges and scaffolding, and, above all, in the convenience of peaceful enjoyment of the building for its legitimate purposes. Of the two methods, patching makes far lighter demands upon the creative abilities of the conservator, and although instances may be quoted of buildings that have been rendered permanently secure by the combined improvement of the material and the adjustment of the stresses by means of a comparatively slight amount of internal reinforcement, it cannot be said that the better and more scientific method has yet achieved complete popular recognition. The patcher still has the dead weight of a bad old tradition behind him, whereas the modern conservator must be prepared to take endless pains in invention and adaptation of means to ends and be misunderstood into the bargain.

Two of the greatest assets of scientific repair are metallic reinforcement and Portland cement. Most ancient buildings fall asunder before actually falling to the ground, and if the several parts are connected with tensile members of

FIG. 36. The fractured frieze of one of the piers at St. Paul's.

FIG. 37. Dislocation of masonry at St. Paul's Cathedral. Right-hand side is dragged down by the weight of the dome. Compare condition of masonry with the statement in the Commission's Final Report on page 128.

adequate strength, equilibrium may be restored and prolonged for a very considerable time.

Buildings erected before the general use of reinforcement may have their strength increased enormously by its introduction, and several metal tie-bars have been put in position in various parts of St. Paul's Cathedral in past times to restrain overturning movements.

Wren's famous reinforcement of the dome and cone is itself evidence of the benefit to be derived from the scientific use of tension members in conjunction with brickwork or masonry, but modern tensional patchings in the building have been little less fragmentary than the usual patchings with compressional material. The metal has been exposed instead of securely imbedded in concrete beams within the interior of the old work, and has been applied in an opportunist fashion just as seemed convenient at any particular moment.

A proposal to treat the building by up-to-date methods would mean, over and above the minute search for all defects, a re-examination of the building with a view to discovering the best places for inserting tensile reinforcement, in the double interest of permanently curing local defects and of compelling different parts of the building, now severed through decay, to act together in future. Certain parts of the fabric could obviously be greatly improved by such means.

The outward leaning walls and west towers might be anchored back to parts of the building at present leaning in the opposite directions. The whole circuit of the outer walls could be united by an endless reinforced concrete beam buried in their thicknesses, and the further distortion and spread of Wren's concealed flying buttresses would be

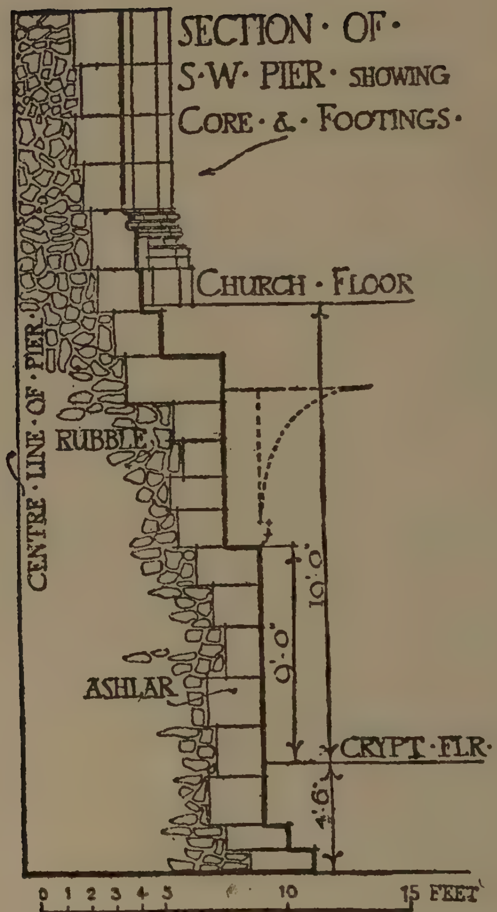

FIG. 38. Diagram showing constructive method unsuitable for the reception of concentrated or eccentric pressures.

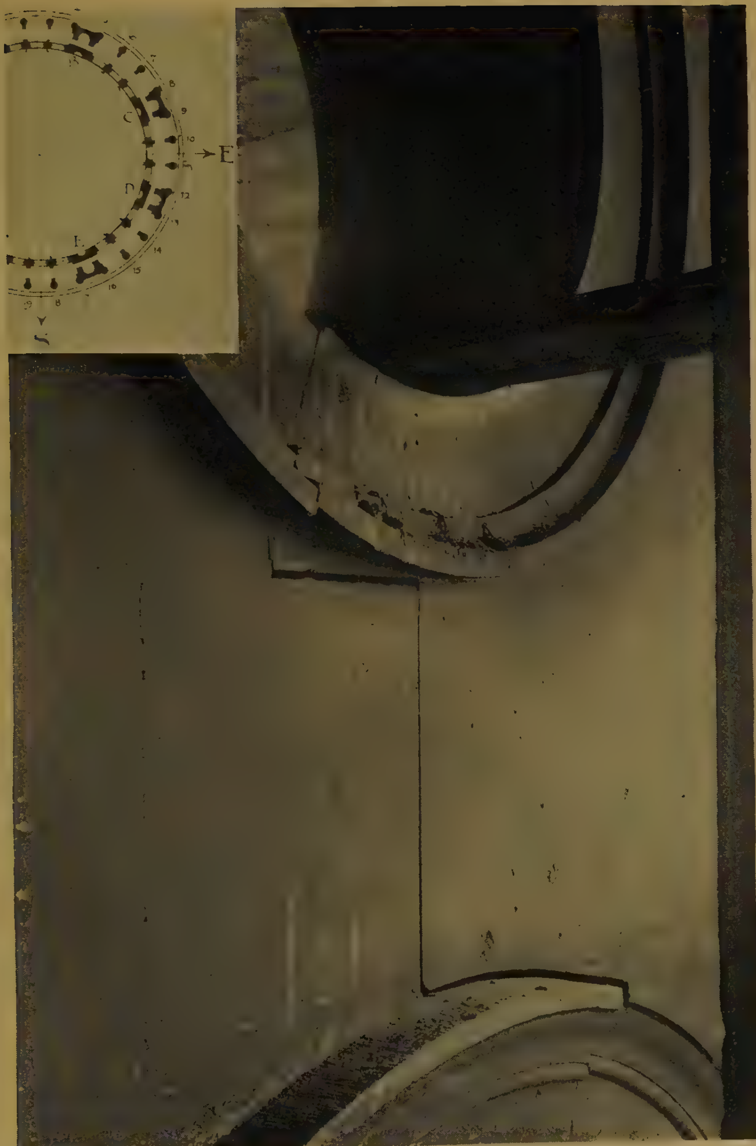

Fig. 39. Unequal loading and settlement open joints in buttresses of peristyle around drum. These cracks are attributed to "cumulative temperature stresses" by the Commission, see page 133.

prevented by this means and by the return ends of the beams at the bastions and at the extremities of the building.

This system of reinforcement, taken together with the strength of the walls, with which it would act in conjunction, would form a secure outer frame within which to attempt the far more difficult repairs required at the centre of the church. A scheme of reinforcement hidden within the defective piers would be preferable both to rebuilding and to the patching-to-death proposals mentioned in the Commission's report, in that the familiar stonework, with all its historical associations, could be retained.

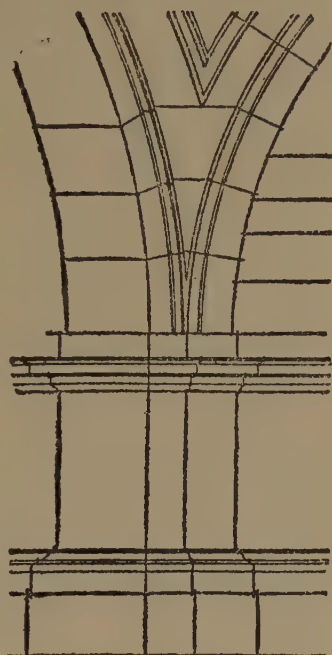

FIG. 40. Diagram showing springing of great arches, designed in a manner which concentrates pressure on one corner of each pier.

Work of this kind has already been successfully performed in the case of the Norman tower piers of Jedburgh Abbey, whose stonework was far more dilapidated than that of the piers of St. Paul's, and given a suitable contrivance of temporary works there is no reason to suppose that the system could not be applied practically to the larger building.

Extensions from the reinforcement of the piers would be

made to traverse the lengths of the main high walls and unite with the reinforcement encircling the exterior.

These measures would restrain the possibility of the ugly and dangerous inward bend of the piers, and prevent the threatened collapse of their important heavily-loaded inner corners by separation from the remainder of the piers.

In combination with the insertion of the reinforcement, the consolidation of the piers would be put in hand on a proper basis, with the removal of the old defective core material and its replacement with new.

Before this attempt could be made important temporary works of shoring and staging would be required, as, indeed, they will be required in the Commission's proposed patching scheme, but their design would be so directed as to be in harmony with the special character of the proposed works. For the safe upholding of the dome, during the operations to the supporting piers, other works would be required beside the staging below the main arches. Absolute steadiness in the superstructure would be essential to the success of the operations, and the apparatus temporarily required to assist in controlling movements in the drums should be devised to become part of the permanent building, and capable of spreading the weight of the high central drums and domes upon the surrounding masonry masses below.

These, as has been mentioned, would have been united previously to one another by reinforcement. What Wren attempted with his thirty-two counterforts of masonry, and failed to achieve through their insufficiency for their purpose, could now be accomplished by adopting the principle of a cone-shaped support that Wren himself designed and used at a higher stage of the building. The outer and inner drums would be connected and in part supported upon a

truncated cone of reinforced concrete whose base would reach to the outer and unloaded portions of the eight main piers upon which the pressures would be more evenly diffused by a base plate of reinforced concrete covering the vaults surrounding the dome.

The base plate would be united at its extremities with the reinforced beams in the wall tops.

The new reinforced cone would be of light construction, but strong by virtue of its shape, and stiffened by diaphragms adjoining and reinforcing the thirty-two defective counterforts.

Above its truncated summit at the level of the dome's clerestory window-sills only local repairs would be needed, though in these reinforcement would be still valuable.

The radial diaphragm walls and counterforts surrounding the inner drum have all separated from it in a greater or lesser degree, for in its descent under the load of cone and lantern it has left the light outer peristyle, or colonnade, at a higher level.

The masonry connections between drum and peristyle which could not withstand the immense tearing strains should be reinforced with non-corrosive metal, since the thickness of the stonework is comparatively slight. Although trivial compared with the serious trouble in the main piers, these defects in the upper portion of the building assume importance because of its exposure to wind-pressure at a great height. Adequate connection of part with part is necessary if destructive vibration is to be avoided.

On the conclusion of the works outlined above the building would be far stronger than at any time in its history, but defective foundations, vibration, and subsidence of the subsoil would still be dangers to be guarded against, and deep digging that would draw water away from under the Cathedral site would have to be prevented for an indefinite period.

IV

HOW TO SAVE THE DOME

THE complete preservation of Wren's great dome is the main object that must be kept in mind. Partial repairs, which confessedly lead towards ultimate demolition and some possible rebuilding of an imitation dome, are altogether contrary to the historical and artistic interests of the building, and are unworthy of consideration. Even financially considered, their cheapness will be costly in the long run.

A scheme in accordance with the principles of archæological conservation and of sound structure, which will not involve the loss of any essential part of Wren's building or interfere in any way with its internal or external appearance, can be designed. The idea of comprehensive consistent control of the pressures in an existing building in a state of decay is a comparatively novel one, which developed in my mind during my exhaustive statical survey of the ruins of Tintern Abbey. Such a scheme is based upon the recognition of the tendencies of all existing masses in the building to fall apart, followed by a reconsideration of the possible functions and action of all these masses if reunited by the introduction of essential connections as determined by the conservator. These essential connections may be either tensional or compressional as indicated by the requirements and the practical possibilities of the case.

At St. Paul's Cathedral, which is principally composed of masonry and rubble set in feeble lime mortar, and is distinctly lacking in coherence, tensional reinforcement will certainly be valuable. Movements in the structure, consequent upon the bursting pressures and arch thrusts created by the enormous weight of the central domes and, in a lesser degree, by the vaults of the lower parts of the church, could be modified by an endless chain of reinforcement buried in

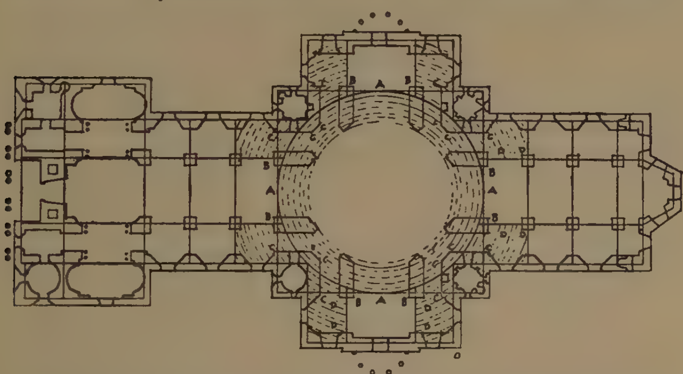

FIG. 41. St. Paul's Cathedral. Suggested main lines of reinforcement to be buried in concrete beams in the wall tops; and plan of reinforced concrete truncated cone to underpin the outer and inner drums and spread their weight over the surrounding masses of masonry. None of these measures will interfere with either the external or internal appearance of the building.

a concrete beam in the interior of the surrounding walls and connected across the building above vault levels. (See plan, Fig. 41.)

The reinforcement would encase the central parts of the building, now spreading away from the axis of the dome, and unite the compressional material into a comparatively rigid base for further operations aiming at the relief of the overburdened and eccentrically loaded central piers. Here

some new compressional members will be required, and a great truncated cone of reinforced concrete would be built

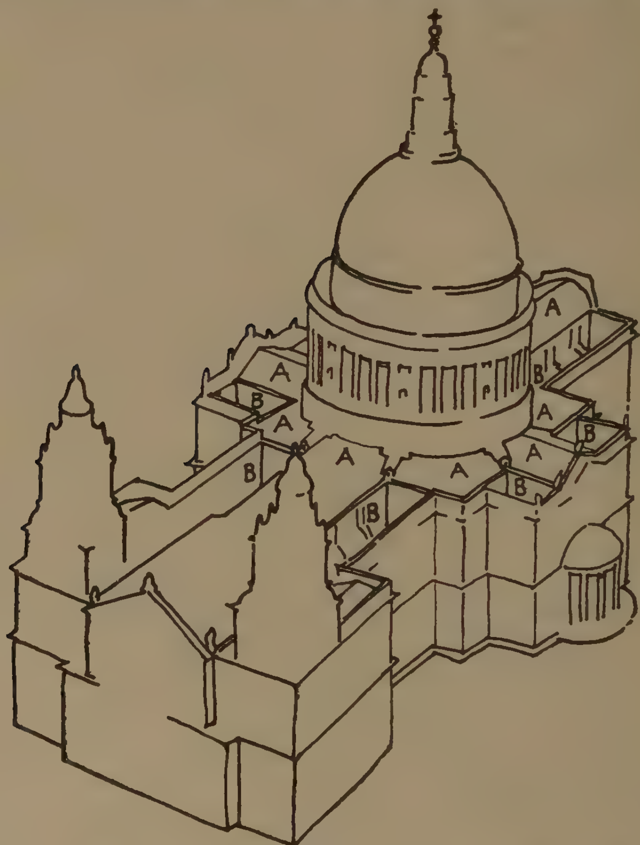

Fig. 42. The conservator's field of operations lies in the interior of walls and piers and in the spaces between the vaults and the roofs A A, and in the areas B B, hidden between the blank high walls of the aisles.

to underpin and receive part of the weights and wind-pressures of the inner and outer drums and distribute them

upon the outer lightly-loaded portions of the piers. It would also spread them over the adjoining masses of the bastions and the ends of the aisle walls.

The preservation of the existing appearances limits the field of operations for the new works to such positions as the interiors of walls and piers, the space between the vaults and roofs, and the eight concealed areas left by Wren between the high blank upper walls of the aisles and the clerestory walls of the nave, choir, and transepts. (See Fig. 42.) Within this permissible zone around the great drums it will be necessary to create a gigantic ferrule, which will provide at once vertical support and resistance to bursting pressure and afford a rigid central node or hub, to which all the other lines of reinforcement of the outer walls will be secured. This zone of operations is not by any means unencumbered, and the minor obstacles, such as stairways, vault fillings, and pavings will complicate the working out of an essentially simple and reasonable proposal. They will not, however, make its accomplishment impossible, for the conservator, while respecting existing arrangements wherever practicable, must be given free use of his discretion in the restricted field of operations allotted to him.

Already some of the minor passages and stairways of the building have been altered by successive surveyors to the fabric on far more slender grounds. In this curious art of conservation, too, apparent obstacles are frequently found to be additional opportunities for knitting the building together. In composing a design for improving the structural condition of the building the larger aspects must be considered first, and the modifications that may be necessary for the application

of the scheme to the existing work are woven in as questions of detail.

The cardinal defect of Wren's beautiful design is not easily grasped from the plan or from those parts of the building ordinarily most frequented. A series of grand arches over the high naves, of small arches over the aisles, and of semi-domes bringing the octagon out to the angles of the circumscribing square all seem to promise adequate spread of thrust and weight. The arrangement of the masses on plan is adroit though overdaring as regards buttressing and diffusing arch thrusts over the foundations of the bastions and the aisle walls, but the vertical component of the weight is not so diffused and rests almost entirely upon the inner corners of the eight main piers.

It is easy now in the light of the great beacon of constructional science erected by the late M. Eiffel to recognize that Wren ought to have made preparation to spread the dead weight of the central domed structure over a wide area of foundations with just the same care that he exercised in diffusing the arch thrusts. His failure to do so occasions the chief deficiency in the structural scheme, but it is quite possible to apply a remedy once the defect is recognized. If the appearance within the building had not been a matter of importance, and if Eiffel had preceded instead of followed Wren, the great architect might have built flying buttress-arches springing from the bastions at ground-floor level and rising up to abut or press against the main piers so as to receive the lines of thrust from the great arches carrying the drums. These buttresses might have carried masonry walls, on their backs, strong enough to conduct some part of the weight of the high central mass down into the masonry of the bastions.

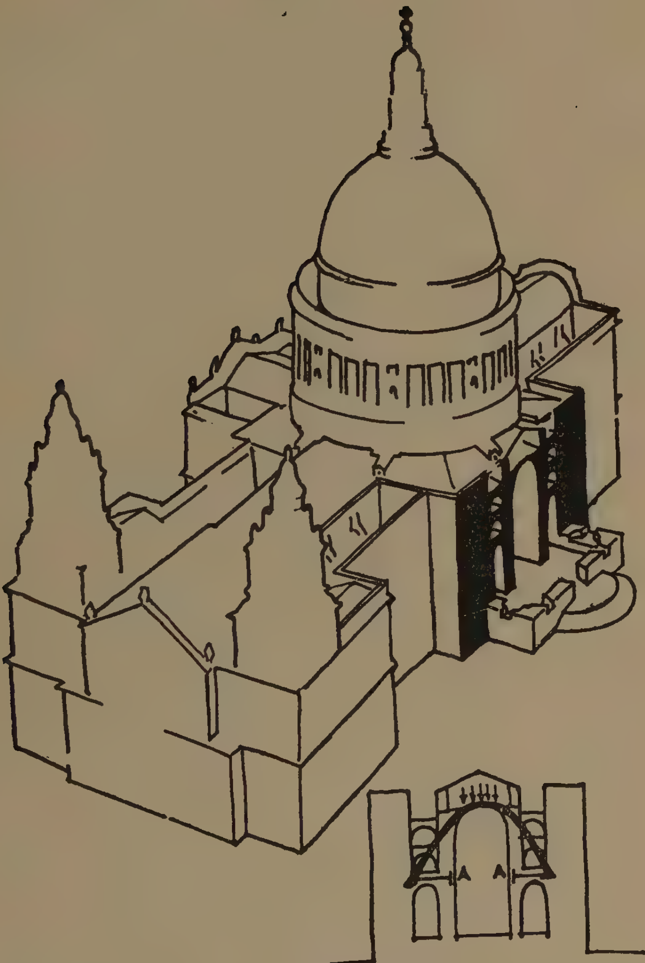

Fig. 43. Round-headed arches over aisles transmit lateral thrusts but are quite incapable of adequately spreading weight. The conic section support in the small diagram could do so. Its abutment would be amplified by anchors in the main piers at A A to restrain their dangerous inward bend.

The steeple of St. Dunstan's in the East (Fig. 44), where a tall tapering central mass is supported upon four arched legs, shows how Wren could spread out weights when he had a mind to, but in the case of his largest work he seems to have ignored alike the opportunity and the need. (See Fig. 43.)

It will not now be permissible at St. Paul's Cathedral to bring the springing of any such buttress support below the aisle vault, but as the aisles are comparatively low a very useful buttress "support" could be built up above the aisle vault. The word "support" is used in place of "arch," because the new structure would be reinforced in such a manner that its lateral thrusts will be minimized.

The support would be blended into the cone and would form a continuation of its surface to the lowest possible point of application. For the sake of clearness the main lines of the supports only are shown on the sketches (Figs. 45 and 46), but the cone as a whole and these four particular lines of it would form a single structural entity. It will be necessary to cut into the substance of certain existing round-headed arches, but not into any that are visible from the floor of the Cathedral. Part of the thrust of these arch-like supports would be usefully absorbed by anchor bars carried into the main piers at a point where they would resist the thrusts of the existing aisle arches. At a later stage of the operations, the metal of these anchor bars would be incorporated with the reinforcement scheme of the piers during their re-coring.

The relationship of these supports to the lines of wall-top reinforcement and the proposed great horizontal tension-ring on the summits of the existing high vaults is shown in Fig. 46. The upper part of the cone is to be carried on as a continuation of the same surface, and will practically take

FIG. 44. The steeple of St. Dunstan's-in-the-East. Illustrating a method used by Wren of distributing weight by inclined supports. He omitted to adopt this method in connection with the arches buttressing the eight main piers of St. Paul's, but attempted to employ it in the upper semi-domes at the four corners of the central part of the building.

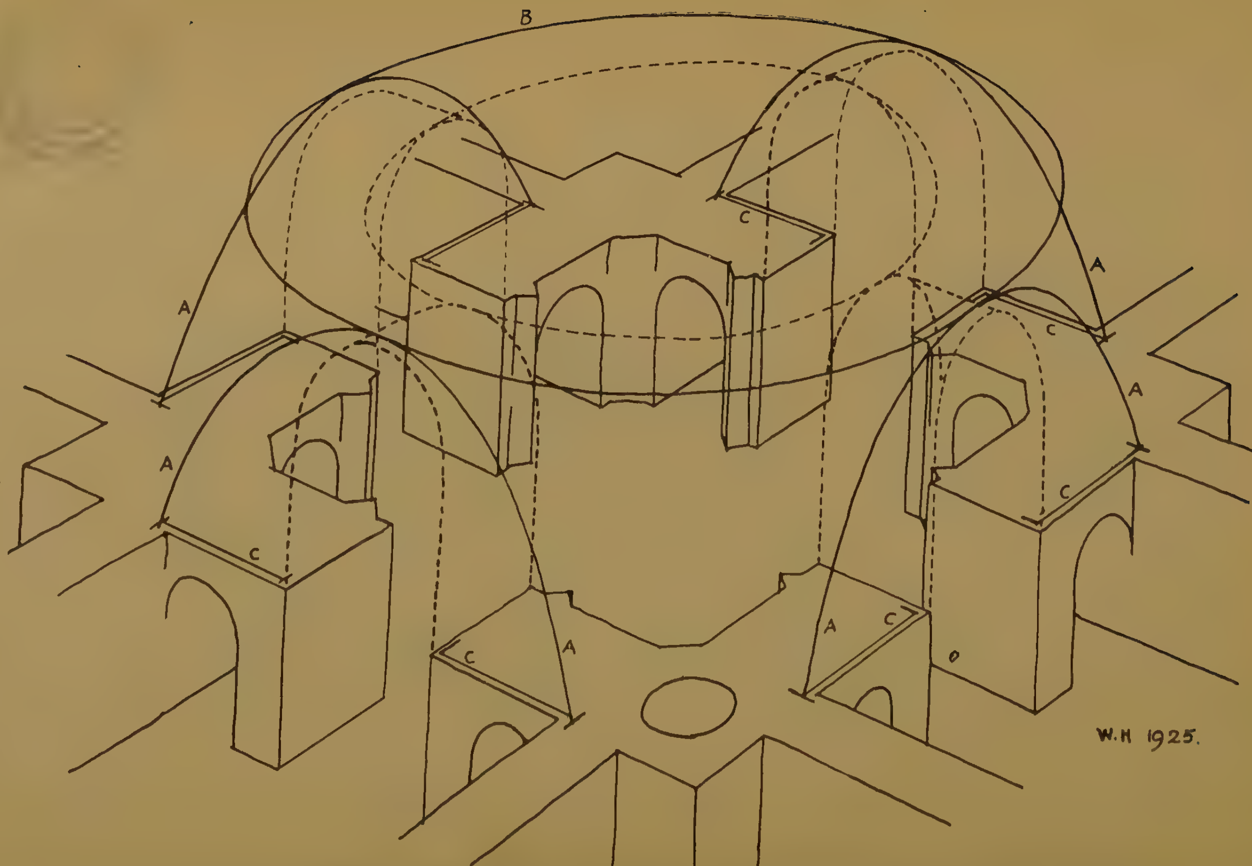

Fig. 45. A A, arch-like supports springing from bastions above the aisle vaults. They would be thickenings of the cone's surface rather than separate members. B, great tension ring above crowns of high vaults which are shown by dotted lines. C C, anchor bars across span of aisles to restrain thrust of A A outward and of aisle vault inward.

the line of the thirty-two existing but defective spur-like counterforts of the dome. The cone will pass right through the outer drum, picking it up and, proceeding upwards, will have its upper rim let in to the masonry of the inner drum, which it will partially underpin. The cone will be a complete circle in plan from its summit at the inner drum down to the level of the top of the high vaults of the nave, choir, and transepts, where it will rest upon the four hyperbolic supports. The cone, however, would not be bounded by these supports as by arch-rings, but would continue to descend as a conical surface bearing upon all existing masonry walls and supports that it passes, until it reaches down to the summit of the aisle vaults. The object of this would be to avoid any concentration of pressure at one limited point of application.

Reference to Fig. 41 will show how the cone bears upon the backs of the great arches at their crowns A A, upon the back unloaded portions of the main piers B B, and upon the bastions C C, upon the high walls of the nave, choir, and transepts at D D, and upon the high upper walls of the aisles at E E. Taken in conjunction with the tensional reinforcement that would have already been inserted around and across the building and which would, to a very great extent, control the thrusts of those portions of the cone below its circular base, this arrangement would spread the weight over the largest possible area.

Wren has provided large masses of solid masonry in the lower parts of the walls, surrounding the building, and by this method the weight of the central portion will be shared among them with a comparatively slight increase of total pressure upon the foundations.

This or some such scheme should be in the mind of the

conservator from the moment that he has convinced himself that temporary patching will not meet the case. Demolition and rebuilding must not be thought of as the only alternative, and it is the duty of all who love the work of our greatest architect to insist that proposals which can only lead to demolition in the future must be abandoned forthwith.

The importance of having a scheme in mind when inspecting the building it is proposed to repair is that it will focus the attention, not only of the conservator himself, but of all those who collaborate with him. To collect details aimlessly with the idea of acquiring information is to amass a dead weight of data without the possibility of assimilation. Imagination and research must go hand in hand, and it is better, even in the interests of the preliminary survey of the building, to make a scheme and then demonstrate its unsuitability than to make no scheme at all. That a Commission could possibly manage to act together long enough and perseveringly enough to survey, analyse, and compose a scheme of repairs for a complex building like St. Paul's is hardly within the range of possibility. Authority must be in the hands of one competent person who will set the problems for his expert advisers to work out in detail. In no other way can considerations of detail be kept in their subordinate place. Admittedly there are lions in the path, and if the details are all considered without reference to the direction and encouragement of some scheme which has at least the apparent promise of success no sufficient weapon will be found to combat them. Armed with a scheme it is a matter of profound interest to ascertain just how it can be applied, and it is only such a sustaining interest that can carry the conservator through the immense fatigue of the long investigation.

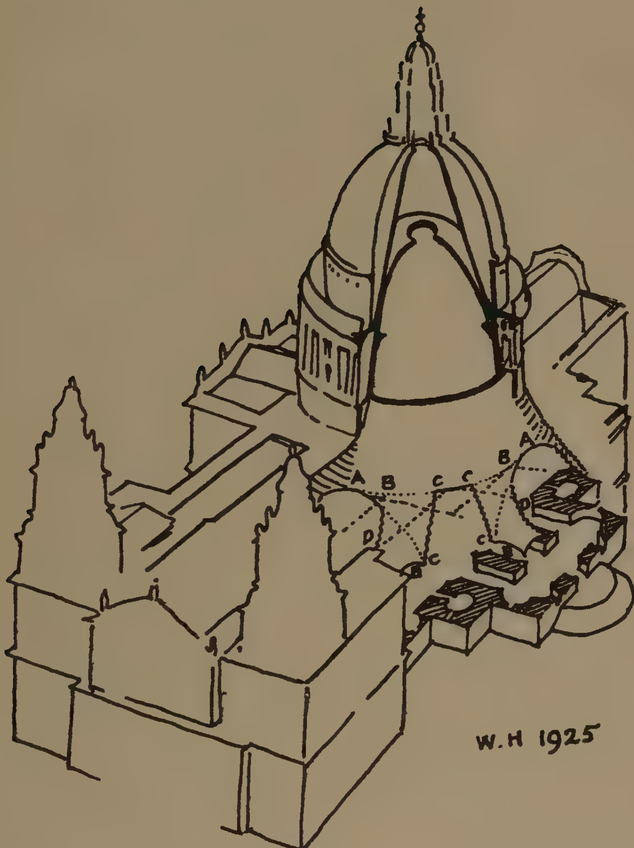

FIG. 46. Principal lines of reinforcement around reinforced concrete cone. Letters A B C, etc., as on Fig. 41.

The scheme outlined would be applied to the building in the following stages; the conservator would first examine all available data, and ascertain what part of the previously acquired information was, in fact, information to him.

Modern engineering is over-specialized in many of its formulæ and methods of expression, and it is essential in dealing with an old structure in a state of partial decay that any statement of fact should be crystal clear to all concerned, and the more complex the subject the more pains must be taken to render its description concise. For this two principal means exist. The preparation of drawings upon which all divergencies from datum are drawn to scale and figured, and the use of experimental models. To stumble about above the vaults of St. Paul's Cathedral in the light of an oil lantern is not an ideal way of acquiring information. The presence of difficulties—the lions above mentioned—may be taken for granted, and every means that will throw light must be used to render them less dangerous.

The conservator will aid himself in forming general ideas by testing his theories as to the building's line of action by applying pressures to experimental models. It is only in this way that the theories of the text-book can be amplified to apply to buildings in a state of partial decay. It must never be assumed that an ancient building, apparently symmetrical in plan, is symmetrical in respect to its structural action. To calculate the pressures of half an arch on the supposition that the other half is similarly stressed is to court disaster, and before any calculation can be put in hand it is necessary to know what the building is doing, and to be in a position to predict what it will do in the future.

Nothing must be left to chance or taken for granted and, as before mentioned, the results of such a survey must be presented in a comprehensible fashion. One of the best ways of presenting the necessary information is to superimpose upon the same drawing the plans of two stages of the building's height, the ground plan being one of them. Fragmentary drawings of parts of the building and drawings made to distorted scales "for clearness sake" are highly deceptive, and do not convey that connected action of bend and drift which goes on throughout a whole building as it settles in response to the various destructive forces of gravitation, wind-pressure, and vibration. (Figs. 55 and 70.)

The reason why the bends and drifts of the building must be studied so closely is that the conservator proposes to anchor back with tensile reinforcement one drifting portion to another, which has an opposite tendency, or is at least sufficiently massive to justify the expense of the operations by a reasonable hope of success. The measure of drift can be estimated from the position of fractures in connection with the positions of deflections from regular alignment and from the vertical, and it is important to mark the positions of all cracks and fractures, however small, upon the survey plan.

These plans should be drawn, in the first instance at all events, to a small scale in fine lines so that the whole building comes under review at the same time. In an approximately symmetrical building like St. Paul's a consistent deviation of all lines towards a single aspect might indicate a bodily sliding down hill, and the vexed question of subsidence through neighbouring deep digging might be settled by means of careful survey plans. By their use also the extent of former damage through whatsoever cause

can be estimated, a matter which affects both the quantity and the position of the proposed reinforcement. In reading survey plans, models made either of uncemented blocks or of plastic material should be referred to, and movements in the structure whose causes have eluded analysis and have remained a mystery when presented in the form of a tabulated list give up their secret under the test of triple cross-reference to the building, the drawings, and the model.

The analysis of pressures is more difficult and less certain in an old building than in connection with a new one. The materials and quality of workmanship differ arbitrarily in different parts of the building, and resistances vary accordingly. Arch-rings must generally be calculated as being separated from their supports right down to the springing, for where the loads are heavy, masonry that might act corbel-fashion at the impost is frequently sheared off, as is, in fact, the case in some of the great arches of St. Paul's.

The recommendations of the usual text-books on Building Construction must be most carefully scrutinized in the light of the actual condition of the building, and a double check, in which a geometrical solution is placed side by side with one obtained by calculation, is distinctly advisable.

In the application of scientific works of repair the aim should be to achieve at least two ends with one effort: the anchor of one system of reinforcement may take the form of reinforcement in a return wall or mass, and reciprocally, or the main bar providing tension between large masses of the building may be made the means of uniting details of masonry traversed in its course.

The order of operations is frequently difficult to determine, but as the details of repair must be worked out in

FIG. 47. A view showing settlement at the level of the main interior cornice, St. Paul's. The dislocation is seen when viewed from one side.

connection with the method of their application, much care must be devoted to arranging this part of the design.

The design of temporary supports for use during the works is also most important from the point of view of convenience as well as strength. At St. Paul's Cathedral lightness is also of the greatest importance, since the foundation is suspected of being weak.

In this connection the question of the spaces between the crypt piers might profitably be decided before any temporary staging is erected, since the foundation for it might be executed as a permanent work forming a raft between the piers, unless the prospect of major works of underpinning should make this course impracticable. In any case the gantry and staging must be devised so as to afford access to the interior of the piers for recoring purposes, and the removal of false work has also to be thought of

All the arches of the dome area, including the alcoves at its corners, will need to be propped up on centres together with the more distant arches above the aisles, that will be cut into by the arch-like supports of the new cone, and these last centres must be made in such a way that the new supports can be inserted without unduly disturbing them.

A cardinal principle of this art of the conservator is that no particle of the old work may be disturbed until something stronger than itself is at hand in perfect order to replace it, and this rule, which must be followed unswervingly in the interests of safety to life and limb, as well as the safety of the building, controls the design of every detail. For a great deal of the reinforcement, which would be undertaken as soon as the centering was erected, standardized units could be prepared. The insertion of reinforcement in the tops of thick walls is not a difficult operation, nor is it particularly

hazardous to place it in the side of a wall that is in reasonably sound condition, so that the preliminary scheme of encircling the building with reinforcement would offer great advantages at a reasonable expense in money and in design. The calculation of the reinforcement for the central hub would be prefaced by the design in detail of the cone in all its aspects, and this would present some extraordinarily interesting features. The actual operations would commence with the insertion of the arch-like supports in stepped seatings prepared for them in the bastions and the adjoining masonry walls. Whether it would be advisable to allow the cone to press directly upon the crowns of the great arches or to wrap them as far down the haunches as they are accessible is one of the details that would have to be decided in connection with the possible retention or alteration of existing staircases, sleeper-walls, and pavings above the vaults.

It is, of course, impossible to indicate these items upon a hastily-drawn sketch. The best method of underpinning the outer drum and of partially supporting the inner drum would also affect the construction of the cone and the nature of its reinforcement, the purpose, the material, and the method of its employment all demanding consideration before a satisfactory solution can be determined.

The erection of the cone would afford an opportunity for setting in order the thirty-two radiating counterforts, now sadly defective, with which Wren surrounded the drums. The absence of any mention of these weight distributors from the Commission's report is an astonishing omission, since the diffusion of pressure is the crux of the whole problem.

V

HOW GREAT BUILDINGS FAIL

EVERYONE knows how a stout wire can be broken at last by repeatedly bending it backwards and forwards at the same point. In more serious investigations of the strengths of materials a similar rule is found to apply, and in the failure of great buildings there comes a time when a slight shock will accomplish at the last what a very great shock could not accomplish in the beginning.

The material will have become weaker with age and the influences of weather and temperature, increasingly riddled with cracks, and worn away by dissolving acids in the atmosphere.

In addition to the fatigue and failure of the material, the building as a whole actually alters very considerably in shape, and, except in the case of a few extraordinary structures specially designed to lock closer as they descend with age and settlement, the alteration is naturally and inevitably for the worse. (Fig. 48.) In the case of piers bending under the lateral thrusts of arches, a continual struggle takes place in which the stages of impending collapse may be diagnosed with some approach to certainty. The decay is often extremely slow, and may affect the shape of the whole pier, subjecting it to a delicate curve before ever a single stone is damaged to any perceptible extent. (Fig. 49.)

Such curves may or may not indicate present danger, for

when they have been produced in the first settlement after construction, further movements may be very slight.

It may be accepted, however, that a curve accidentally

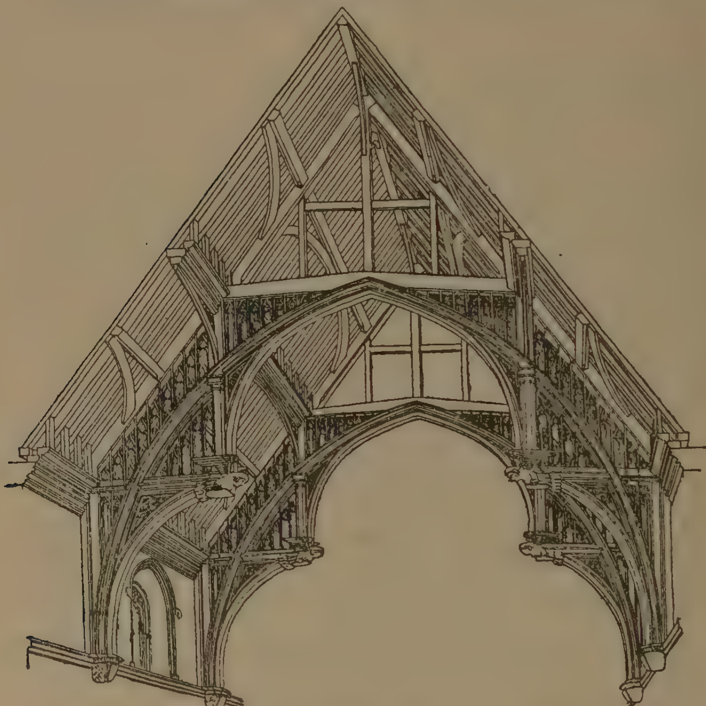

FIG. 48. The timbers of Westminster Hall were so balanced as to knit closer together as they shrunk with age. Such skilful construction is altogether unusual. Even in Westminster Hall the descending movement soon became excessive and dangerous.

produced in a part of a building which should be straight is a warning that further movements in the same direction are at least probable, and that if they are not now taking place they may do so in the future.

Bending accompanied by the fracture of stonework is a sign of more advanced decay in which the movements of large masses are accompanied by the weakening of details of the building and their separate and piecemeal destruction. (Fig. 50.)

When a building has arrived at this stage any signs of continued movement and fracture are serious indeed unless some satisfactory explanation can be found which makes it appear that the defect is, after all, of a purely local or temporary character.

Wren was able to face the cracking and patching of one of the piers of St. Paul's dome, and yet at the end of a long life could find the heart to exclaim : " If I glory, it is in the singular mercy of God, who has enabled me to begin and to finish my great work so conformably to the ancient and true model." But in his time it was reasonable to suppose that initial settlement was a sufficient explanation of the fractures, and that movements would cease when the building had taken its bearings To-day, after two hundred years have elapsed, this theory is no longer tenable, and it has become customary to blame the rubble core of the piers as practically the sole cause of trouble, and to assume that any means of strengthening the core will restore the building to a condition " as sound as it was in Wren's time." Though this is not, after all, so great an assumption when the history of continual repatching is remembered, the statement is most dangerously optimistic, and this brings up the subject of the human element in the failure of great buildings.

Important national monuments fail and come crashing to the ground, not because there is no responsible person in charge, but because of the irresistible temptation to an optimistic frame of mind. Old buildings can stand a most

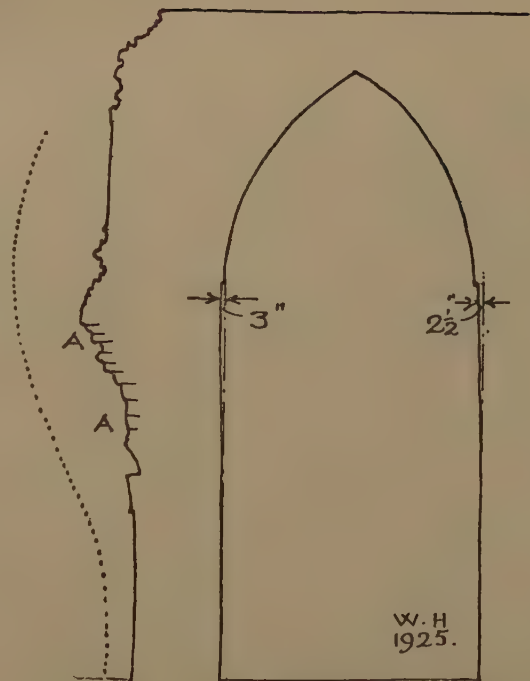

Fig. 49. Tintern Abbey. North-west pier of crossing. The pier is bending and leans over 3 in. The dotted line shows the nature of its curve. No stone is fractured, but cracks appeared in the joints at A A.

Fig. 50. When a wall carried upon arches bulges and overhangs its base it may crack open at a convex point in its curve A. At the same time it may displace and crush individual stones at B.

extraordinary amount of damage before they finally fall, and it is not realized until after the event that their approaching end had really been announced by unmistakable premonitions ; had those in charge been able to read them.

Sometimes the architect in charge of an historical building is a keen student of archæology, and is interested in the art of the period in which the building was erected. It does not follow, however, that the secrets of its methods of building and their peculiar strength or weakness are familiar to him, for these interesting details are not recorded in books, and only reveal themselves to the most diligent and persistent inquiry and research conducted on historical and on structural lines. No custodian of a famous building wishes to obtain the reputation of scaremonger, and it is difficult for any person who has lived a long time in daily association with an apparently massive monument to make up his mind to the fact that the normal routine of minor patchings must be abandoned at a given moment, and a far-reaching scheme of major works substituted for it. And if he finds it hard to come to a decision, it is also extremely difficult for him to obtain expert assistance in the matter.

The men who are fitted by nature and training to survey, examine, and analyse the structural condition of an ancient building are few and far between, and eminent skill in the design and construction of new works is not necessarily a qualification for this highly specialized branch of structural engineering.

To seek expert advice on ancient buildings from famous engineers and architects in busy practice is neither fair to the building nor to these eminent gentlemen themselves, and the committee-meeting procedure is altogether absurd in such a case.

The nature of the advice that will be given is practically a foregone conclusion. The recommendations are likely to be more polite than efficient, and are sure to be directed once more towards neatness rather than strength. The social, as well as the structural aspect, is considered, and the interest of keeping things going in a pleasant groove is allowed undue sway in deciding upon measures of repair.

It is quite natural also for the experts called in to wish to apply some specific remedy that has been proved effective in other constructional works, and as the repair of ancient buildings is not an everyday affair with them, the most suitable means are not likely to be chosen. For instance, grouting with liquid cement injected into fissured masses of masonry has proved beneficial in certain cases. Grouting by gravitation, followed by a tamping process in which the cement is forced home into the heart of the work, is also a valuable aid to the conservator, but at St. Paul's Cathedral conditions exist which make both processes impracticable, as the sole measures of repair, and the attempt to apply them would defeat its own object.

The danger of partial repairs, of superficial repairs, executed in the interests of neatness, and even of thoroughly conscientious repairs applied in ignorance of the real needs of the building, is their deceptive appearance of strength.

A new stone placed in a hole from which an old one has been cut out may seem thoroughly sound, not because it is bravely contributing to the support of the work, but for the exactly contrary reason. It has not cracked simply because it has been impossible to insert it under the pressure to which the old one was subjected, and its sound appearance is merely an indication of its idleness, the adjoining old stones

having to take the share of weight that should press upon the new one. (Fig. 51.)

At St. Paul's Cathedral it is possible to inspect a thin thread-like crack in the masonry, and recognize in it an evidence of recent movement, but it is not so easy to realize the magnitude of that movement.

The broken stone may or may not be part of the original structure, and if it be a patch, at what time was it inserted? And what was the condition of the cracked stone it was put in to replace?

To obtain a just estimate of the total extent of the cracks in the pier it would be necessary to add to the size of those now showing, the breadths of the historical fractures that have been obliterated, and this can now only be arrived at as a personal estimate, a sage guess on the part of any individual surveyor. (Fig. 52.)

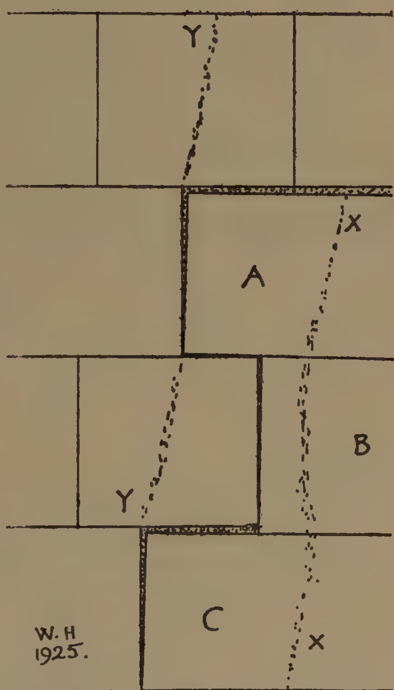

FIG. 51. New stones, A B C, put in to replace stones fractured by crack X X, settle upon their beds and cause fracture Y Y in adjoining old masonry.

To make such estimates, and to make them credible to other experts, and to those in control of the repair fund, are two very different things, for in regard to ancient buildings the accepted philosophy seems to be that "when they are up they are up, and when they are down they are down," notwithstanding the warnings of experts who have been able to calculate the potential state of collapse in the structure

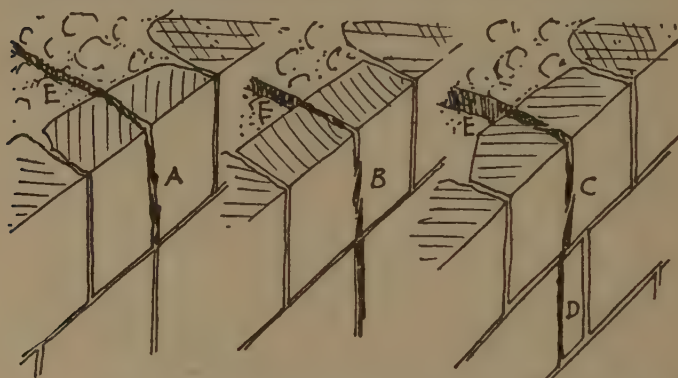

FIG. 52. Original stone A cracks in settlement and is replaced by B, which cracks in turn and is replaced by C, which is now found to be cracked. The internal fracture E is very considerably wider than the outward appearance of fracture on C. A small patch is put in for neatness at D.

before its actual fall. The destruction of the campanile at Venice is said to have been the subject of earnest remonstrance from one member of the commission of architects in charge of it during the last few months before it piled itself neatly in the piazza San Marco, but the warnings were received with incredulity and ridicule. A great tower standing up straight on its foundations does seem to give the lie to theoretical calculations proving its inability to do so.

It is the time element in the decay of large structures

that makes for confusion in the minds of the custodians and the public.

The final plunge may, indeed, be instantaneous. A few

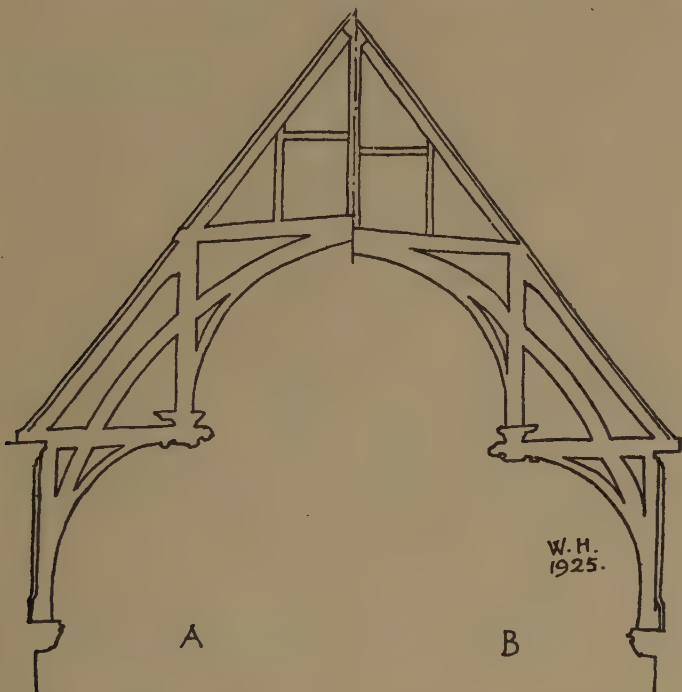

FIG. 53. Westminster Hall Roof. A shows design drawn in accordance with the slope of the gable wall. B shows its present decrepit state as surveyed when on the point of collapse prior to recent repair.

plucky photographers, perhaps, record the falling fragments in mid air, but the thing is done in a flash. But while the fall is sudden, the manœuvring of the masses into the position ready for a fall may be extremely slow.

Thus the roof of Westminster Hall, which was repaired just in time to save a sudden crash, had descended at its ridge 18 in., and at hammer-beam level by about a foot, without actually coming to the ground. (Fig. 53.)

At Rievaulx Abbey a wall 130 ft. long, 60 ft. high, and 5 ft. thick, and overhanging its base by 2 ft. 6½ in., was found to be steadily moving in the direction of its overhang, and was tearing free from adjoining masses of masonry at

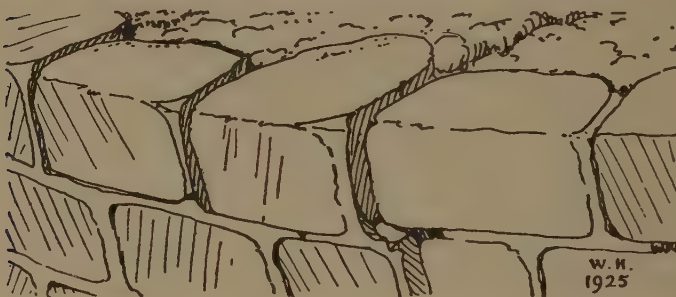

Fig. 54. Stones in wall top being carried out of position by movements in the overhanging wall. Cement pointing of a superficial character had been applied to repair the work(!), but only served to indicate the direction and the rapidity of the movement.

its ends. Repairs that had been executed in recent times had proved powerless to arrest the movement, and these modern patchings only served to show the amount of movement in different portions of the wall. The pointing in cement mortar, while it demonstrated the recent nature of the repair, also permitted of measurements being taken of the gap between the pointing and the original place in which it had been inserted some few years previously. (Fig. 54.)

Still the wall had not fallen, though a diagram prepared to show its state of balance proved how perilously near it had come to the overturning point.

In this connection it should be noted that a wall does not need to be in what is known to the science of mechanics as a state of "unstable equilibrium" before it begins to move. A comparatively slight excess of material on one side will draw it gently over until a state of instability is produced.

Movements of the wall at Rievaulx persisted during the erection of temporary shores, and only the insertion of two reinforced concrete beams in the body of the old work prevented a disaster when a fierce gale coincided in point of time with the repair work applied to a dangerously shattered spandril of the arcade. The solid masonry of the upper part of the wall cracked through cement joints and stones indifferently, and the wall was only prevented from overturning by the hold of the reinforcing rods of steel.

Reinforcement has been adversely criticized on the grounds that it is "out of sympathy with the principles of Gothic work," although the tie-bars of Westminster Abbey may be cited in contradiction of this theory, but no other means could have been effective at Rievaulx that would not have obscured the interest of the ancient architecture.

The nature of movements in old buildings is not always so easily comprehensible as it was in this case. An unbuttressed tower pier at Tintern Abbey was found to be moving in response, as it seemed, to the eccentric load of a large outcorbelled fragment of masonry and to the pressure of a great arch of the tower. The condition of stability was calculated under these conditions, and repairs were put in hand, but further movements were discovered. The pier bent and opened out into a series of fine hair cracks, and on a resurvey of the whole building it was discovered that a general drift of many heavy masses was taking place which tended

to augment the burden of the bending and collapsing pier. Here again reinforcement inserted in a beam concealed in the wall top and connected with anchors in a distant part of the building restrained the movement and cured the trouble. (Fig. 55.)

FIG. 55. Tintern Abbey. Outline of north chancel wall. The buttress at the east end stands practically upright, but each pier leans towards the west, drawn over by the failure of the north-west pier of the crossing A, which has been left unbuttressed by the fall of the north high wall of the nave.

At the risk of repetition it must be pointed out that a knowledge of the whole building and its tendencies is necessary in forming an estimate of the danger occasioned by a series of defects in one of its parts.

So sympathetic are the several masses of a vaulted building to each other that at Rievaulx Abbey simultaneous fractures took place at a distance of 110 ft. from one another, one being near a point where dangerous works of underpinning were proceeding, and the other at a point in the wall where

the overhang was almost negligible. A statement to the effect that "the golden cross of St. Paul's stands as high as ever it did" is mere nonsense when viewed in the light of the settlements that have taken place below, for every part of the building has sunk upon itself as well as upon the piers, whose damaged state has recently become a matter of public knowledge.

The amount of movement in a new building as it settles on its foundations is rarely, if ever, made the subject of accurate measurement, and, indeed, the idea of movement at all hardly enters into the ordinary builder's calculations except in the case where new work has to be made to bond and line up with old.

Indifference on the subject is due in part to the fact that where buildings are small and light in proportion to the strength of their materials the movements are extremely slight. Where weights are heavy they become pronounced, and where the weight is heavy and eccentrically placed in regard to the supports it will subject them to overturning action and to excessive settlement simultaneously in such a manner as will burst them in pieces in course of time.

A foreknowledge of such possible movements, their source of origin, direction and extent, is a necessary ingredient in the preparation of designs for the intelligent conservation of St. Paul's Cathedral. The assumption that good modern materials and "modern science" will prevent movement is only partially true.

The movement in sound modern works may be comparatively slight, but such as it is it must be prepared for. The time has come perilously near when any further movement in the eight main piers will be uncontrollable, decisive, and final.

VI

THE CONSERVATOR'S ART

THE art of conservation of ancient buildings differs from ordinary architecture and constructional engineering in that it demands a more subtle and a more sympathetic and accommodating outlook upon the work in hand. Its object is to maintain present appearances and old associations while removing the element of danger and imparting the largest practicable measure of permanent stability to the existing structure.

Where the creative designer of new works naturally desires to erect buildings of great cost and conspicuous aspect, the conservator seeks to keep the measures he employs as subordinate and as inconspicuous as possible. Several special difficulties have to be met in carrying out this ideal in practice, and not the least of them is the difficulty of maintaining the bulk and weight of the building during the insertion of the hidden internal means of repair.

The conservator is nearly always forced to look upon the constructional arts from an inverted point of view. The weight of the old building is already in position, suspended overhead in a perilous state, for his services are not required when the supports are safe, and there it must be maintained by temporary works until the concealed permanent reinforcements can be threaded into position and securely affixed to the ancient masses of material. (Fig. 56.)

FIG. 56. Repairs to Jedburgh Abbey Church. Steel needles inserted in the old masonry to carry its weight during re-coring operations to the piers undertaken by H.M. Office of Works.

Reproduced by permission of "The Builder."

FIG. 57. Metal cramps Z were used in the construction of ancient buildings to hold the blocks of marble together. Rods A B C have been used in repairs to hold up stones in detail. Cramp X X would not prevent movements at Y Y. Movements P Q R S can only be restrained by thoroughly systematic reinforcement of the whole building.

For such works no conventional rule can be established, there is no orthodox beginning and end, the upper parts of the work may have to be finished before the new foundations are started, and all things supported from gantries and stagings until the whole is completed. For all this seemingly strange disorder the works must be designed and applied in a thoroughly scientific manner.

The means of repair are calculated with all, and more than all, the care that would be required in connection with new works, and are applied in a manner that leaves nothing to chance.

In a succession of great progressive experiments on ancient works where loads of hundreds and even thousands of tons of masonry have been involved in serious movements, the various devices, instruments, and methods of repair have been brought up towards perfection. From the insertion of a few metal bars, cramp fashion, to aid in the consolidation of a bad local defect, or to secure an out-jutting single stone, the systematic reinforcement of a whole building has been evolved by slow degrees. The process was not taken up eagerly as a pet new scheme, but has been adopted slowly and almost perforce to meet emergencies altogether beyond the compass of other or ordinary measures of repair. (Fig. 57.)

The use of a specific means of repair as a nostrum for universal application has no place in the science of conservation, where the guiding principle is that the means shall be adapted to the needs, and it was by working upon this principle that the need for reinforcement in certain cases revealed itself experimentally.

About sixteen years ago the ideal of complete conservation had been proposed in connection with the repair of

historic buildings, and internal consolidation was suggested as the appropriate means to this end.

If homogeneity could be attained the old building would

Fig. 58. Ruined Church, Castle Rock, Mistra, Greece. Small dome hanging in the air stuck together with tenacious mortar. From a sketch by the author.

"stick together like a single stone," and if only a sufficient amount of high-grade cement could be inserted into the

interior of the work it was supposed that homogeneity would surely ensue. In that belief I visited Southern Europe and the Near East to study adhesive construction, and found some most astonishing evidences in favour of the principle of homogeneity.

Small Byzantine buildings with half their principal supports demolished by earthquakes still held their little domes aloft with the piers between their drum windows hanging pendant in empty air like the ribs of an open umbrella. (Fig. 58.) But what is possible as a freak of Nature in connection with a miniature mountain chapel is not necessarily applicable to a building of much greater scale and weight. The principles of tenacity, adhesion, and homogeneity in building are intensely valuable in the

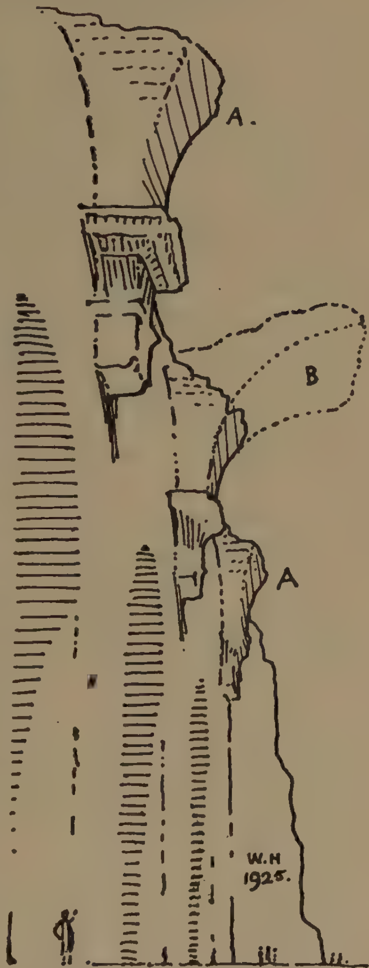

FIG. 59. Projecting masses like that at A can be seen in the ruins of Roman buildings. Projections like that at B would overtax the tenacity of the strongest cement except in buildings of very small scale.

large building as well as in the small one, but they are not to be worked out by the same simple means. The great Pantheon, for all its tenacious Roman mortar, and its admirable structural disposition of parts, exhibited cracks from which the trifling chapels were free.

Many colossal Roman works can show masses of concrete and concrete-like brickwork jutting out beyond the line of the substructure after the removal of some part of their support, but as the scale of the building increases the relative size of such out-corbelled masses grows less and less in proportion, and though the good qualities of Roman mortar and Roman exploitation of them are amply demonstrated, there are limits to the size and weight of a projecting mass that can be supported by cement adhesion alone. Beyond a certain point the tensile stresses become too great for cement and demand reinforcement if the ideal of homogeneity is to be maintained. (Fig. 59.)

Experience in the conservation of ancient buildings by internal consolidation points in the same direction. In light and small works lime-mortar may be all that is needed, or cement grout applied by hand or machine may suffice. In large works where great masses are moving the soundest stone and cement is snapped like barley sugar, and to advocate grouting in such cases is an idle waste of breath. To apply it is a waste of money and, worse still, of precious time, while the movements in the building go slowly and inexorably from bad to worse.

Without an exhaustive analysis of all the conditions applying to the piers of St. Paul's Cathedral it would be impossible to say exactly what measure of reinforcement must be used to increase their strength to a degree that will cover present and future needs with a reasonable margin of safety. That

grouting should suffice of itself to consolidate the core is unthinkable, for, even if the grout could turn the material within the piers into a perfect concrete by filling every interstice and adhering to every surface, new cracks would

FIG. 60. Even when the cement grout A has penetrated an old fissure and adhered to the surfaces of the old stone fragments, these surface layers can still part from the mass. This applies particularly at St. Paul's, where the core contains lime mortar and stone of a chalky nature.

be formed by the simple process of cleaving the surface layers from the old mortar and chalky stone. (See Fig. 60.)

When the time comes for the piers to be examined in

detail they will be found to be acting, not as single homogeneous masses, but as more or less consistently disunited groups of piers split apart by the thrusts of the imposts of the great arches. The inner corners of the piers are being forced down and in towards the centres of the high naves, while the outer corners are pressing out on to the buttressing masses. The stresses tending to separate the several parts of the piers are in active operation, and grout inserted to fill a fissure would probably be shaken free from one side or the other as soon as it was set.

In determining the amount of reinforcement required in any part of an old building to which a conservation scheme is to be applied minute calculations are needed. But before calculations can profitably be taken in hand it is necessary to know just where the reinforcement will be capable of doing the utmost good to the structure.

In these investigations experimental models are invaluable, not that they solve the mathematical problems, but that they enunciate or assist in enunciating them in a perfectly lucid manner. The track of principal pressures through the building should be ascertained by noting the behaviour of loaded plastic models whose material will compress in response to pressure, and confirmed by models of loose blocks which will tilt when the pressures are not applied directly upon them.

Wren's method of spreading the weight of the dome drums upon his arches, semi-domes, piers, and bastions, has been a puzzle to some engineers, and the exact apportionment of pressures is still open to analysis. Here again experimental models will assist in clearing away needless uncertainties and contradictions even if they are not used in a final estimate of pressures.

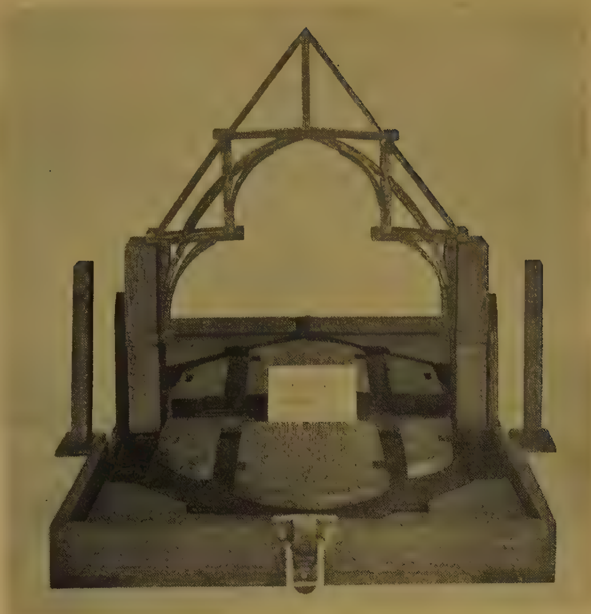

Fig. 61. Model made of loose blocks to indicate how the timbers of Westminster Hall roof take their loads.

Fig. 62.
The same model with parts of its structure removed.

The Author's model is now exhibited at the Science Museum, South Kensington.

Reproduced by permission of the "R.I.B.A. Journal."

FIG. 63. The same model with alternate supports in position. The substitution of one member for another makes it clear that all are useful.

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It has been stated as a fact that Wren's thirty-two counterforts were really intended to spread weight and modify the violence of the eccentric application of the load upon the tops of the piers. It is my firm conviction that he so regarded them and that within the measure of their strength they have so acted, and, although reduced in strength by fracture, they are still so acting. This view is not acceptable to some constructional engineers, who declare that a "buttress" should be used to resist thrust and cannot spread a weight, and that they "would like to cut away the 'buttresses' and free the arches of a useless load."

Who will believe calculations expressed in decimals of a ton, where the very functions of constructional members are a matter of controversy? A collapsible model on the lines of that designed by me to show the balance action of Westminster Hall roof timbers would soon set the question at rest, and such a model should be made before anyone gets to work carving Wren's design and increasing the degree of eccentricity of the load upon the piers. (Figs. 61, 62, 63.)

The model would be built up with alternative possibilities of action with or without the counterforts, and would be useful also in demonstrating the possible increased efficiency of the "buttresses" if strengthened with reinforcement at their bases, or by an encircling and uniting cone, or by both these members as suggested above in the third chapter. (Figs. 64, 65, 66.)

Some degree of unanimity among engineers will be required if the repairs of the great monument are to meet with general approval, and the use of models is distinctly worth while. In this connection I have been assured in reply to my inquiries that investigations upon models carefully made to scale could be undertaken at the National Physical Laboratory at Teddington.

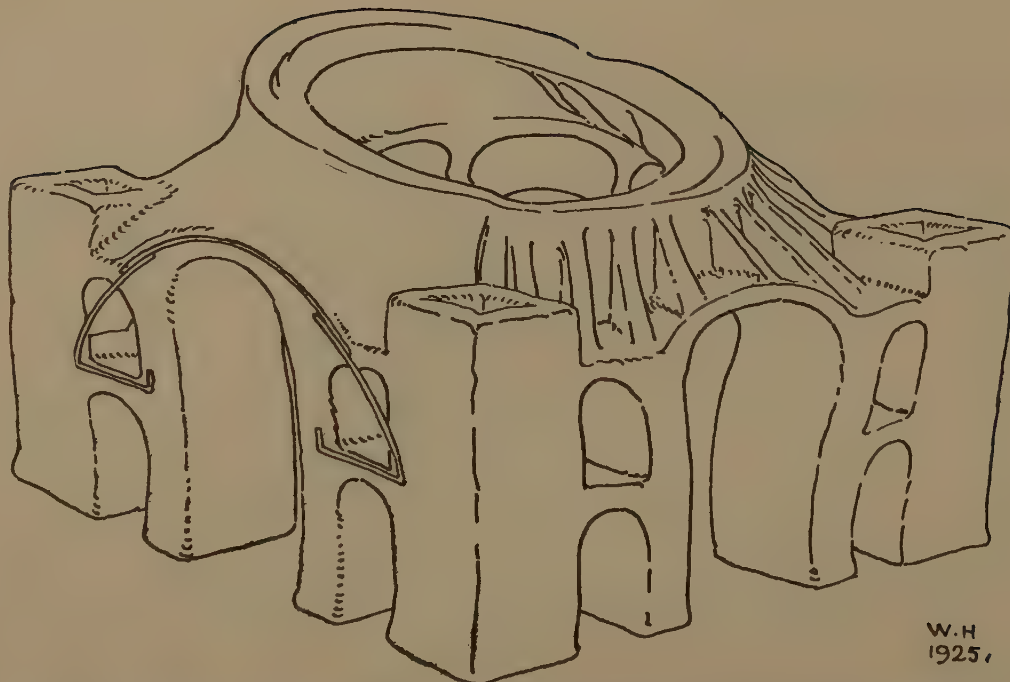

Fig. 64. Plastic model half provided with slips of thick paper representing the cone and its hyperbolic supports and half as at present. The value of the cone is shown in the lesser degree of distortion in height and in the shape of the arches.

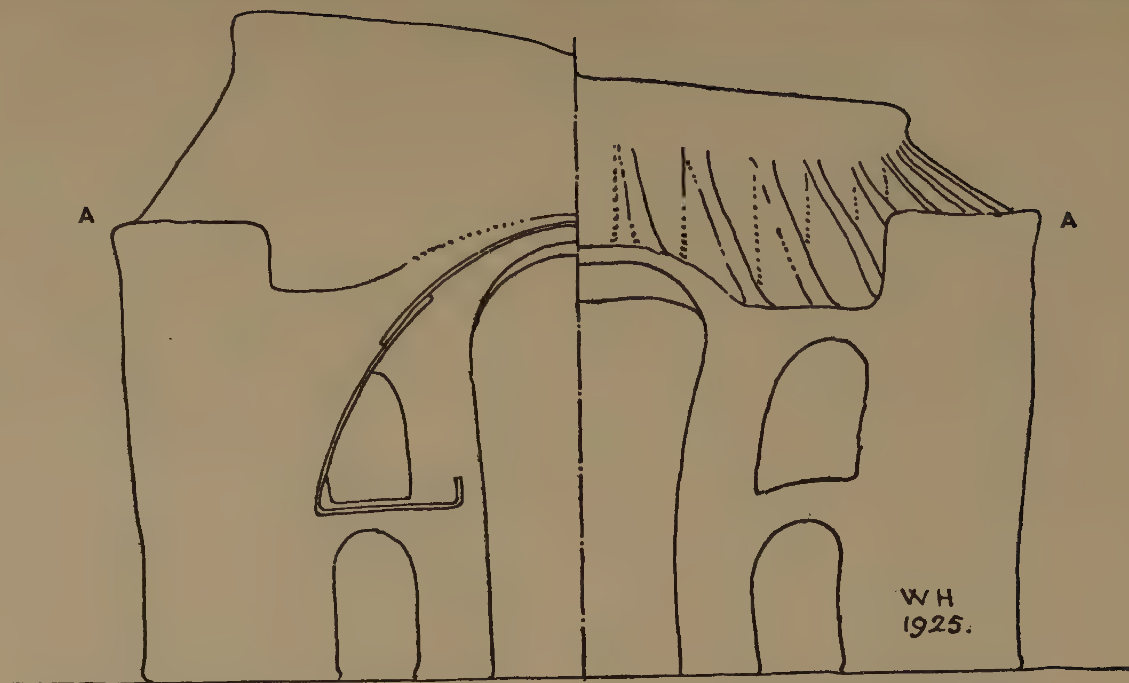

FIG. 65. Plastic model; side with paper cone inserted.

FIG. 66. Plastic model without cone.

Both sides were loaded evenly at start. No reinforcement was used at A A in order to test bastion abutments. Models of a much more detailed character could be made and tested under skilled observation at the National Physical Laboratory, Teddington.

As eminent architects and engineers have expressed widely divergent views concerning the methods to be adopted, an independent investigation by this responsible National institution would be the most reasonable way of composing differences and arriving at a scheme that will afford the complete and lasting preservation of St. Paul's Cathedral.

To a certain extent it is necessary for the modern conservator to be himself and to have confidence in his own ways of thought.

If he possesses greater faith in steel and reinforced concrete than Wren was in a position to confess to (before these materials were introduced into construction) it is quite legitimate and logical that they should be employed in the service of Wren's cathedral if, and when, the need arises for their use.

A sentimental clinging to old-fashioned methods of repair by traditional or, rather, historical building practices is also right where they can be employed with safety, but the choice of methods and of material means must be guided by the requirements of the case.

The conservator will not pledge himself to conform to any mock sentimental limitation that requires him to use lime-mortar just because Wren used it, nor use cement grout just because it is up to date, or was considered to be so some sixteen years ago. In the several parts of a complex building there may well be some stones that need refixing where lime-mortar will be an admirable bedding material. In other places cement grouting applied by gravitation or by pressure will be both useful and appropriate. In some places cracked facing stones may need replacement with new, but all these specific remedies muts be adopted as and

where they meet the needs, and not because of preconceived aws laid down by the conservator for his own guidance.

In these works the rule must be to study the building and let it suggest the best possible course of repair that can be applied without damage to its appearance. Limitation to the use of lime-mortar would mean erecting new additions of stonework about Wren's piers, and the insertion of pressure arches across the building under the great arches to restrain their inward bend. It would also mean blocking up the adjoining spans of the aisle arcades to improve the buttress action of the building in upholding the main piers against the thrusts of the arches and pendentives. If lime-mortar were insisted upon as the only proper bedding and uniting material, repairs at St. Paul's Cathedral would necessarily take some such form to the immense damage of the building as a work of art.

The conservator must use appropriate means—modern means—such as can be calculated and understood by modern advisers, and his archæological researches should be directed towards understanding the structural needs of a building erected under a different system of structural articulation.

The artistic side of conservation is not, however, altogether negative, and artistic considerations govern the adoption of one or another of two alternative schemes, as has been seen in the case of the proposal to use only lime-built masonry, which may be suited to repairs in a small building, but not to meet extraordinary pressures in a large one. One point upon which artistry and construction are in agreement is the advisability of keeping new steelwork out of sight and out of contact with the air.

VII

THE BENEFITS AND ECONOMY OF CONSERVATION

CONSERVATION work is not cheap in the sense that the usual opportunist patching of old buildings may be cheap.

The measures are difficult to design and to execute, and since they must be based upon certain knowledge of the present state of the building and its probable future movements, the cost of the preliminary survey will be considerable.

The stagings and temporary centres also have to be far stronger than would be required for new works, and their design demands extraordinary care and foresight to fit them for their purpose and for the special nature of the proposed operations. It is, of course, quite unusual for a staging in ordinary building construction to be required to carry the weight of the whole upper portion of a building, and the conservator's staging naturally figures as an expensive item in comparison with gantries and centres in normal use.

A sound scheme developed in accordance with the principles of conservation is, nevertheless, likely to prove economical in comparison with a proposal to demolish a large building, for it obviates the handling of thousands of tons of material in their removal and descent to ground level, in demolition, and their reassembly, ascent, and fixing in re-erection.

FIG. 67. Melrose Abbey. The projecting masses of masonry are retained by internal reinforcement which does not intrude itself upon the exterior appearance of the building and is protected from the weather. The repairs were devised and executed by H.M. Office of Works, Historic Buildings Branch. From a water-colour drawing by the author.

Reproduced by permission of "The Builder."

Fig. 68. Jedburgh Abbey. Norman pier re-cored with reinforced concrete by H.M. Office of Works. The original fractured facing stones are retained safely in position with all their historic and artistic interest. The disintegrated interior was completely removed and replaced with concrete suitably reinforced. From a water-colour drawing by the author.

Reproduced by permission of "The Builder."

FIG. 69. Kelso Abbey. Unsatisfactory Repairs. From a water-colour drawing by the author.

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In the central part of St. Paul's Cathedral, where sixty-seven thousand tons would have to be dealt with, and where the heights are also very great, demolition is to be avoided on the prosaic ground of cost alone, even if sentimental, artistic, and historical associations made no appeal for the conservation of the authentic ancient architecture.

The illustrations Figs. 67 and 68 show how by careful conservation and internal reinforcement the ancient appearance of the work can be retained. Fig. 69 is an "awful example" of the effect produced by ill-considered measures of repair where the steel reinforcement has been applied on the exterior of the stone-work and is exposed to the weather.

And though the cost of conservation is considerable, its benefits are still more so. While demolition entails the need of re-erection, and patching can only be regarded as a temporary measure of doubtful, and generally delusive, character, a well designed scheme of conservation may not only improve upon the strength of the building in its state of decay, but may make it stronger than it was when first erected.

To demolish and reconstruct St. Paul's Cathedral to the same design, but with piers built in Portland stone, instead of with a rubble core, would be to invite a repetition on a somewhat modified scale of just those defects that are becoming apparent to-day, and for which the general interrelation of parts throughout the whole building is responsible.

But by insisting that all the existing masses of the present building shall contribute to the strength of the whole, and by scientifically designing and supplying just those necessary links of new material that will contribute to this end, the steady increase of such characteristic defects may be arrested.

The science of construction in England has not altogether lost the impetus given to it by the theory and practice of Sir

Christopher Wren, and the inevitable changes of two hundred years would give to the detailed examination of St. Paul's great scientific value and interest.

The relative strength that can be obtained by modern or ancient methods or materials must be compared during the preliminary inquiry in connection with a conservation scheme, and the investigation would be worth making upon such general grounds and for the increased knowledge that would be obtained of great masses of material under the test of actual practice.

The partial failure of Wren's building demonstrates his scientific economy of material, and its examination in detail can throw a light upon the behaviour of other economically designed structures that will have far-reaching effects upon constructional theory. The practice of conservation of other partially ruined buildings will also be established upon a firmer basis, and among the benefits and economies of conservation this scientific aspect must not be forgotten.

At present engineers are not even agreed as to the lines of thrust throughout the building, nor upon the meaning of some of Wren's several constructional devices, and though the retention of Wren's noble building is the main object, it cannot be doubted for a moment that modern constructional science would benefit by the preservation of St. Paul's Cathedral if this were to be undertaken on the lines of complete conservation. So-called preservation by patching will yield no such benefits.

APPENDIX

THE final report recently published by the Commission of Experts appointed in 1921 to investigate the structural condition of the dome of St. Paul's will do rather less than nothing to restore public confidence either in the present state of the Cathedral or in the prospect of its receiving adequate repair at the hands of the Commission.

The text of the report, in which we have inserted cross-headings, is as follows :—

19 Queen Anne's Gate, Westminster, London, S.W.
February 14, 1925.

To the Very Reverend the Dean and Chapter of St. Paul's.

ST. PAUL'S CATHEDRAL.

Gentlemen,—Your Commission, in pursuance of the reference to them in October, 1921, "to examine the building and to advise what methods should be adopted for its preservation," now submit their report giving the result of their investigations into the condition of the Cathedral, together with an account of the observations that have been made and reasons for the conclusions arrived at, and for the recommendations made.

Your Commission held its first meeting on October 28, 1921, when it was unanimously agreed that the chair should be taken by Sir Aston Webb, K.C.V.O., P.R.A., F.R.I.B.A. About fifty meetings have been held, and individual members of the Commission have, in addition, paid many visits to the Cathedral to inspect work in progress or to render themselves familiar with particular aspects of the problem under review.

Your Commission's investigations up to the present have

been mainly directed to the condition of the structure under and composing the great dome. The surveyor to the fabric, Mr. Mervyn Macartney, F.R.I.B.A., placed before the Commission, of which he is a member, all the available data in the shape of drawings and reports made in the past, which were carefully examined and perused. It then became clear to your Commission that there was an absence of precise data as to the condition of the dome structure, and also an absence of accurate levels and measurements from which it would have been possible to ascertain definitely what movements, if any, had been taking place in the structure. As a consequence, a great deal of the valuable investigations made by previous Commissions could not be utilized fully owing to the lack of a reliable datum system for comparison.

One exception to this was the installation of plugs inserted, under advice given prior to 1914, at each side of cracks throughout the fabric of the Cathedral. These plugs were designed to carry micrometer gauges from which variations in the cracks in three dimensions could be ascertained. Observations with these gauges had been made and recorded between the years 1914 and 1920, though, unfortunately, not continuously.

At an early stage of your Commission's investigations it was apparent that there were visual signs of damage in the masonry of the dome supports, in the buttresses and elsewhere, and that settlements that had occurred during construction had been corrected by levelling up courses of masonry. They, therefore, ordered a thorough examination and survey of the dome structure to be made and recorded. This was done at the end of 1921 and during the first three months of 1922. The immediate conclusion arrived at from this examination was that settlements of a regular and irregular character had occurred in the past, mainly ascribable to compression of the ground, but there was a complete absence of evidence that any settlements in the foundations

were taking place, or, in fact, had taken place during recent years. This conclusion is formulated in your Commission's first interim report of June 1, 1922.

Although no evidence of recent movement in the foundations existed, it was felt that, if settlement was not taking place, positive evidence to that effect was essential. With this object in view, and also to provide a reliable basis for comparative measurements of other movements in the Cathedral, your Commission directed that a system of reference points permanently embedded in the masonry of the Cathedral should be installed, whereby levels and measurements could be observed by means of precision instruments and recorded for future comparison. The installation of this system was effected during the latter half of 1922, and since then three complete series of observations and measurements have been made at approximately six months' intervals.

Scope of Investigations.

The investigations of your Commission may be divided broadly as follows: the integrity of the foundations; the movements of the dome structure; and the stresses in the masonry of the dome and its supports.

A portion of the preliminary examination ordered by your Commission was the taking of levels on various masonry courses at different heights in the Cathedral—namely, on the impost in the crypt, the plinth of the church floor, the plinth of the main cornice, the attic cornice itself, the benches in the Whispering Gallery, and masonry beds in the stone gallery and the lantern. These levels showed that there is a departure from the horizontal of these courses, intended to be built horizontally, which becomes progressively less from stage to stage until at the lantern it is negligible. Similar indications were found as the result of plumbing the dome structure from the top of the lantern.

The testimony of these observations, which in your Commission's judgment is important, is that the settlement took place during the progress of the construction, and was irregular, in consequence of the lack of uniformity in the subsoil both as regards its strata and its previous compression under old St. Paul's. This settlement produced a tilt of the structure towards the south-west, which became more pronounced as more and more weight was placed on the foundations. In addition to the evidence of the rectification of levels mentioned in the previous paragraph, there is further evidence, such as the insertion of compensating courses, that the effect of this settlement was corrected at the completion of each important stage in the construction—such as the main cornice, the stone gallery, and the parapets adjoining the external drum. In short, the greater part of the tilting observable to-day occurred during construction and was rectified from stage to stage; the true measure of the subsidence and tilting that has taken place since the completion of the building is the deviation of the base and axis of the lantern from the horizontal and the vertical respectively, and there is no such deviation.

For an accurate system of levelling it was necessary that a permanent bench mark or reference point away from and uninfluenced by possible movements of the ground near the Cathedral should be available, and by the courtesy of the Post Office authorities this bench mark has been established on a disused cast-iron shaft penetrating into the London clay near the General Post Office. About 150 gun-metal sockets, specially designed to take hardened steel plugs for supporting levelling staves, have been inserted in appropriate positions in the masonry of the Cathedral. By this means direct comparison is always possible between one series of levelling and another.

Throughout the series of careful observations taken during 1923 and 1924 no relative settlement between the piers and other portions of the Cathedral fabric have been observed.

It can, therefore, be stated with confidence that no settlements of the foundations are taking place at the present time.

Your Commission recommend that this levelling and plumbing should be repeated, completely or partly as circumstances may direct, at suitable intervals of time, so that the inception of any general or relative settlement of the foundations may be detected as soon as possible. They are of opinion that an appropriate time for the next complete series would be in the early spring of this year. Your Commission further recommend that, as in the past, a very jealous eye should be kept on all building operations in the vicinity of the Cathedral, which might alter the condition of the subsoil, with disastrous results.

Effect of Temperature Changes.

The observations of the micrometer gauges recorded between the years 1914 and 1920 on the cracks in the drums supporting the dome indicated that an annual opening and closing of the cracks with a seasonal sequence, as well as a slow but definite steady increase in the width of each crack, was taking place. The opening and closing would indicate respectively an annual contraction and expansion of the masonry of the drums due to temperature changes, and the increase a slow and progressive horizontal increase in circumference of the whole dome structure.

Careful measurements of the diameters of the drums made in the spring of 1922 reveal a distortion of shape consistent with a gradual increase of circumference, and the shape of the structure at the Whispering Gallery level showed distinct deviations from a true circle, with definite bulges over the north, south, east, and west great arches. Part of this deviation may be due to the effects of settlement during construction, but most of it, especially the bulges over the

arches, is due to the cumulative effect of temperature changes. The north and south diameter was $6\frac{1}{4}$ in. greater than that from the east-north-east to west-south-west, and it may be reasonably inferred from this and the general shape of the Whispering Gallery that the expansion between the north and south has been greater than that between east and west, the movement having been towards the south.

The levelling sockets, twenty-four in number, embedded in the masonry of the Whispering Gallery, also carry reference points, between which precision measurements of 12 diameters across the inner drum have been made by an Invar tape under constant tension. These measurements confirm the distortion of shape previously noticed; these 12 diameters are prolonged at each end across the corridor surrounding the Whispering Gallery by measurements between reference plugs embedded in the masonry of the corridor.

The precision measurements reveal that there is a periodic alteration in the length of the drum diameters, and the evidence is that the main temperature change is an annual one, the structure tending to resume the same shape at the same time of the year. There is insufficient evidence as yet to ascribe a value to the cumulative effect or progressive increase. The dimensions of these movements are roughly as follows: Alteration of diameter of Whispering Gallery, ·005 ft. (say $\frac{1}{16}$ in.) at a maximum point; alteration in the distance across the corridor between inner and outer drums, ·001 ft. (say $\frac{1}{80}$ in.).

In connection with the scheme of measurements, clamps for securing plumb-wires have been embedded in the masonry at the top of the cone, in the keystones of each of the four open great arches, and in the main cornice at the top of each pier. Observation with the precision plumb-bob suspended from these points have indicated the following movements: The top of the cone moves backwards and forwards under temperature changes, the range of movement

being about ·01 ft., or, say, ⅛ in. The period seems to be an annual one. The keystones of the great arches move in sympathy with the alterations in diameter of the Whispering Gallery, but not to the same extent. The piers have a slight annual oscillation, but the movement is very small.

As a reference basis for the linear measurements and plumbing, gun-metal plugs have been embedded in the masonry of the bastions at church floor level, from which measurements are made by an Invar tape to the intersection of two lines engraved on the brass plate at the centre of the church floor.

The reference points for linear measurement, and the plumb-wires have been co-ordinated with the centre of the church floor by observation with theodolites, by which means not only the amounts, but also the direction, of the differences found between series of observations can be ascertained and recorded.

To sum up the results of the observations just described, the weight of evidence points to a periodic alteration in the shape of the fabric, undoubtedly due to the effects of temperature changes, but it is difficult to form an accurate quantitative estimate of this alteration, as its magnitude is of the same order as that of the accuracy of the apparatus employed. The periodic alteration in shape due to temperature changes is a natural one, and any attempt to restrain it would either be abortive, or, if partially successful in any part, would be liable to bring dangerous stresses upon some other portion of the fabric. The case is quite different, however, as regards the cumulative effect or progressive increase; evidence exists that such an increase is taking place, and steps should be taken to arrest it.

Your Commission, therefore, recommend that in order to eliminate or minimize any progressive increase, systems of metal hooping, one encircling the inner drum and another the peristyle or outer drum, at about the Whispering Gallery level, should be provided.

Weight of Dome Structure.

Turning now to the weight of the dome structure as a whole, your Commission agree with and have adopted the calculations of Mr. J. D. Drower, F.S.I., made in January 1914 and August 1921. The total weight of the dome, its drum and peristyle, the buttresses surrounding it, the eight piers supporting it, and the eight great arches, together with those portions of the walls and vaults of the choir, nave, transepts, and aisles carried by the piers and bastions, may be summarized as follows :—

	Tons.
1. Total from top of cross to top of keys of great arches	23,098
From top of keys of great arches to top of plinth, 4 ft. 2 in. above church floor level ...	28,116
2. Total from top of cross to church floor plinth ...	51,214
From church floor plinth to underside of foundations	16,056
3. Total weight upon earth ascribable to the weight of the dome and its supports ...	67,270

The portion of the dome structure above the attic cornice consists, as to its lower part, of two circular walls or drums resting on the piers and bastions and the arches between them. The inner wall is a truncated cone with a batter of one in twelve, an internal diameter at the base of about 112 ft., and a total height of a little over 90 ft. from the top of the main arches to the passage around the base of the dome. The top of this inner drum forms the support of the interior dome and the brick cone which carries the lantern and the outer dome. The outer drum is cylindrical with an outside diameter of nearly 140 ft., a height of about 39 ft. to the base of the peristyle columns, and an additional height to the top of the stone gallery parapet of about 54 ft. There

is a distance of a little over 6 ft. between the drums at the level of the tops of the main arches, and they are joined by thirty-two radial cross walls, which are continued outside the outer drum in the form of buttresses.

There is little doubt that the weight of the drum comprising the peristyle and that of the inner drum with its top burden act independently, as, owing to the cracks in the thirty-two radial walls between the two drums, there is practically no physical connection between them. The cracks in these radial walls appear to be due to cumulative temperature stresses rather than to unequal settlement, as there is no vertical displacement relatively in these walls at their base.

The shattered condition of the masonry of some of the thirty-two buttresses placed around the outer periphery of the peristyle has been noted in many previous reports on the safety of the Cathedral. These buttresses do not play an important part in transmitting weight to the bastions, nor, in your Commission's judgment, is it desirable that they should.

The combined load of the dome structure is carried by the piers and the bastions, but the independence of action above alluded to is responsible for a certain concentration of loading on the inner drum. The problem as to what is the distribution of weight between the piers and bastions is one which, in the judgment of your Commission, does not in the present condition of the structure admit of an accurate solution. The design is such that the greater part of the weight of the dome structure is carried by the piers.

Distribution of Weight.

Suggestions have been made from time to time that more weight should be spread over the large area of masonry composing the bastions. In the opinion of your Commission, this transference of weight would be undesirable. The Cathedral is partly founded upon ground consolidated by Old St. Paul's; the amount and extent of this consolidation is a matter of conjecture. The evidence is that considerable

settlement took place during construction, but that a state of equilibrium has now been reached. Any considerable change in the disposition of loading would undoubtedly upset the balance and be productive of further settlement.

With the exception of the radial walls between the inner and outer drums, which have already been mentioned, the masonry above the level of the keystones of the great arches appears to be in sound condition, and there is every reason to suppose that the "great chain" round the base of the cone is still efficiently fulfilling its task.

A careful examination was made of the masonry composing the great arches, and on the whole it is in good condition, such cracks and fissures as were apparent being recorded on drawings left in the custody of the surveyor to the fabric. For reasons that will be given immediately, your Commission do not consider that these cracks jeopardize the integrity of the dome structure.

Reference has been made to the concentration of loading on the inner drums, but your Commission hold the view that natural internal arch action in the lower part of the inner drum below the great windows, about 40 ft. in depth, has the effect of transmitting the weight borne by the piers directly to them without making great demands upon the ribs of the main arches themselves.

In the judgment of your Commission the horizontal plane of loading, that is the ruling one, and therefore most necessary to consider, is that passing through the springing of the main arches. Statements have been put forward that the stress on the most highly-loaded portion of this plane is about fifty tons to the square foot, but with these statements your Commission do not in any way agree, as such a condition of loading must assume that the whole of the weight of the inner dome structure, amounting to about 14,000 tons, is completely carried on the front ribs of the main arches and transmitted solely by those ribs to a very small area at the inner ends of the tops of the piers.

The assumption in the preceding paragraph makes no allowance for the arching effect previously mentioned, nor for any part of the weight of the inner structure of the dome reaching behind the front ribs of the main arches and being transmitted to the bastions. An estimate of the distribution of the weight can only be a matter of opinion and judgment, but it is not over-stating the case to say that the stress intensity of fifty tons per square foot alluded to above is reduced to one-half this amount, or less, if due allowance be made for the increased area of the pier at the ruling plane which would be brought into action in consequence of the above considerations.

It is to be noted that sample 8 in. cubes of Portland stone from the Cathedral, tested at the National Physical Laboratory, did not crack until subjected to a load of 400 tons per square foot, and crushed under loads of from 430 to 490 tons per square foot.

A careful examination was made of the condition of the masonry composing the eight main piers supporting the drums and dome. These piers consist of an outer skin of Portland stone ashlar set in lime mortar. The ashlar is worked in conformity with the architectural features of these piers, but the breadth on the bed varies considerably. The interior of the piers is uncoursed rubble masonry of many kinds of stone bedded in the same kind of mortar. This mortar, which, for its effective setting requires to be exposed to the atmosphere, has not properly consolidated in the interior, owing, doubtless, to the fact that the piers being of considerable thickness, the atmosphere has been excluded from the interior by the hardening of the mortar in the joints of the ashlar casing.

The ashlar masonry is worked so as to show close joints on the face, which in many instances has resulted in the spalling or flaking of the edge of the stone, owing to a concentration of pressure at these places. At the level of the church floor plinth the load of 51,214 tons has been

estimated by Mr. Drower to be carried as to 37,984 tons by the eight piers, and as to 13,230 tons by the four bastions. On this assumption the loading of piers at this plane is about fifteen tons to a square foot averaged over their area.

In the crypt the load on each pier is greater, but the area of the piers is also greater, and the incidence of the load more favourable. It is probable, therefore, that the maximum intensity of stress at this portion of the structure does not reach so high a figure as at the church floor plinth. Under the footings the load on the earth has been calculated by Mr. Drower to be just over five tons per square foot under the piers.

Grouting the Piers.

The main question during these necessary investigations, to which your Commission has given much anxious consideration, after ascertaining the actual facts as existing at present, is the stability of the eight piers carrying the dome, and how far their structure, as previously described, is, or could be made, capable of resisting the pressure to which they are subjected.

Schemes for entirely rebuilding the piers have had most careful consideration, but to replace the existing piers with others, without taking down the dome, would entail transferring the load on to temporary supports. This operation, in the opinion of your Commission, would be attended by the very gravest risk, and they have arrived at the definite conclusion that any attempt to rebuild the piers would inevitably affect the foundations, at present stable, and the results would be disastrous.

The fact that no movement has been observed in recent years in the foundations led your Commission to make a large number of experiments with various forms of grouting with a view to ascertaining whether the piers could be satisfactorily consolidated by this method, which is on somewhat similar lines to that recommended by Sir Francis Fox some

years ago. Beginning in the crypt, a number of boreholes were drilled through the pier. From these boreholes cores were removed which gave clear information as to the material of which the piers were built and the extent of any cavities which exist.

This investigation showed that the construction of the piers in the crypt was, on the whole, satisfactory. After thorough washing out these boreholes were grouted by the cementation process, using very dilute grout. A subsequent investigation of the interior of the piers showed that the grouting had successfully filled the small cavities existing. It was, however, found that some of the face stones had been embedded in plaster of Paris, and the washing out under pressure had, unfortunately, had a very deleterious effect on this plaster. Similar experiments were carried out in one of the piers above the church floor. Here, also, many face stones are bedded in plaster of Paris, and it was, therefore, decided that the grouting must be carried out with richer grout. A number of holes were drilled from each side of the pier to within a short distance of the opposite side. These boreholes were bored in a systematic manner, beginning at the bottom and about 3 ft. to 4 ft. apart vertically. These holes were grouted at various pressures up to 50 lb. per square inch, grouting being continued until no further grout could be injected. The grout often appeared from holes at a higher level than that at which the injection was taking place. A subsequent opening out of parts of the face work showed that this grouting method had also been successful in filling the cavities and binding together the internal aggregate. This is the method which your Commission recommend should be carried out throughout the piers, with the addition that suitable reinforcing bars should be introduced into the boreholes before grouting is complete. After this has been done any shattered or defective face stones can be removed without danger and replaced by stones of suitable depth.

Summary of Recommendations.

The possible effect of vibration has been investigated by the National Physical Laboratory and subsequently confirmed by Mr. Mallock, and the conclusion arrived at is that no deleterious effect is taking place from this cause. Your Commission's recommendations may therefore be summarized as follows :—

1. To consolidate the piers by grouting through boreholes on similar lines to the method adopted on the north-east transept pier already referred to, by strengthening the pier temporarily with steel and timber casing during the process, and by reinforcing the piers with metal rods embedded in the boreholes, to be followed by replacement of any defective ashlar.

2. To encircle the drums of the dome with metal hooping to check any possible cumulative increase in circumference of this fabric.

3. To repeat at, say, six-monthly intervals the series of levelling observations and also the plumbing and other measurements described in the report and for which special instruments have been provided.

4. To guard against danger accruing from building operations in the immediate vicinity and below the level of the foundations of the Cathedral.

Your Commission are of opinion that, if the work advised by them is carried out, the piers will be brought into a condition at least as good as at their original construction. They do not believe that a complete reconstruction of the piers and their foundations is advisable or necessary, and they wish definitely to disassociate themselves from any proposals of this nature.

We are, gentlemen, yours faithfully,

Aston Webb.
Basil Mott.
E. C. Trench.
G. W. Humphreys.
Mervyn E. Macartney.

Like the second interim report, the present pronouncement contains abundant evidence of the Commission's unfamiliarity with the class of problem with which it has attempted to grapple, but the greater length and more detailed character of the new document makes the fact still more startlingly clear. Surprisingly clear, indeed, for it might have been expected that investigations carried on in the building for a prolonged period would have served to introduce the subject and familiarize its main aspects even to persons formerly unacquainted with the survey and analysis of arched and vaulted buildings in a state of decay.

Perhaps the most valuable result that can be hoped for from the publication of the report will be a public recognition of the fact that the statical analysis of historical buildings is a special branch of constructional science for which a special and intensive training is necessary.

A patient whose leg is broken does not go out of his way to call in the services of a heart specialist, but though in medicine the principle is recognized that special training is necessary for the acquirement of particular skill, this principle has not been applied to architecture.

It will be quite sufficiently difficult to estimate the extent of the danger and damage at St. Paul's even when the best of knowledge and experience is applied to the case, and without these special qualifications the task will be altogether insuperable.

The state of St. Paul's is not such as will warrant indefinite procrastination, for, whether the Commission can see them or not, signs exist of serious movement which cannot be disregarded if the destruction of the building is to be avoided.

In spite of the recent assertions that the proposals contained in the second interim report would amply suffice to meet all the needs of the case, the Commission now proposes to augment its grouting and patching scheme by reinforcing the piers and by banding the drums of the dome. These concessions to criticism may be viewed in one of two lights,

for they may indicate a genuine change of mind upon the dangers and necessities of the case, though it seems far more probable that they should be attributed to an attempt to satisfy the opposition that was very properly stirred up by the patching scheme. In either case the vacillation of the Commission in eating its words and changing face at the eleventh hour would give very little cause for increased confidence, even were the proposed additional measures themselves acceptable on structural grounds.

On the subject of the reinforcement to be threaded into the boreholes made for applying grout to the piers, I feel privileged to speak, for I invented this special method in 1916 in connection with a proposal to strengthen the north-west pier of the crossing at Tintern Abbey.

The method was not adopted in that particular instance on account of the difficulty anticipated in obtaining complete unity of action between the metal and the rubble core of the pier, although my proposal had been to make the boreholes large enough to tamp in cement around the rods by means of a sleeve device slipped over each rod in turn.

The danger of this use of reinforcement inserted under conditions which make its action highly uncertain is that, like the other recommendations of the Commission, it is likely to inspire false and wholly unwarranted confidence.

To this objection must be added the equally important consideration that, until the building has been properly analysed as a whole, neither the Commission nor anyone else can possibly know how much, or how little, reinforcement will be needed, and, in a word, the additional strength will be altogether an affair of guesswork. As the originator of the method, I am probably as favourably inclined to the use of this form of reinforcement as anyone can reasonably be, but I should certainly hesitate to experiment in the first instance upon St. Paul's Cathedral.

The Commission has also adopted the "tension ring" suggested in my article of January 21, 1925, in "The

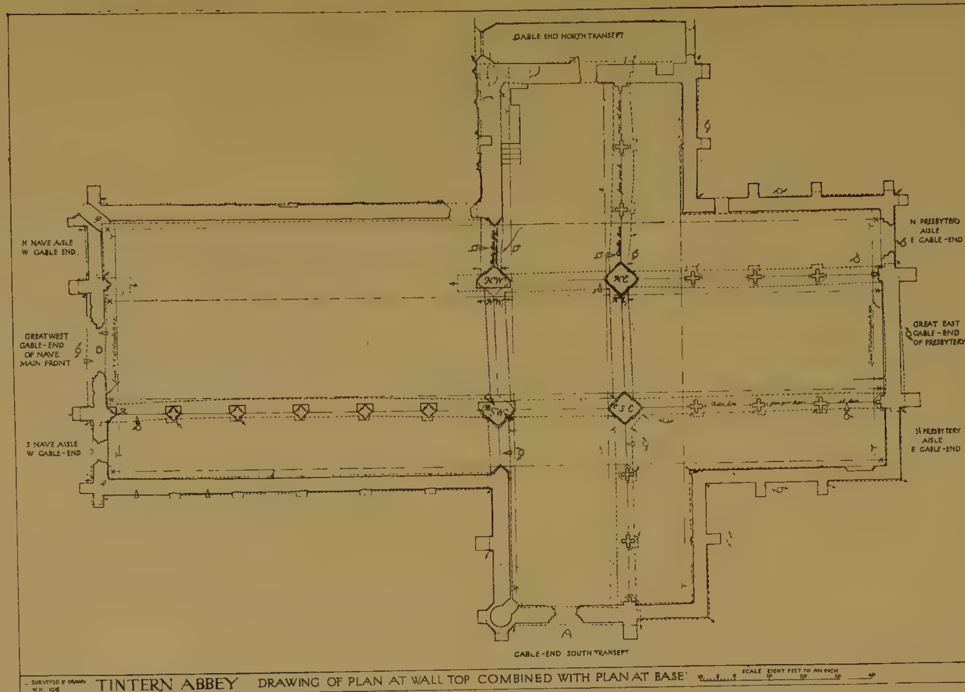

Fig. 70. The small arrows indicate the direction of principal movements. Wedges show the positions of fractures in the masonry.

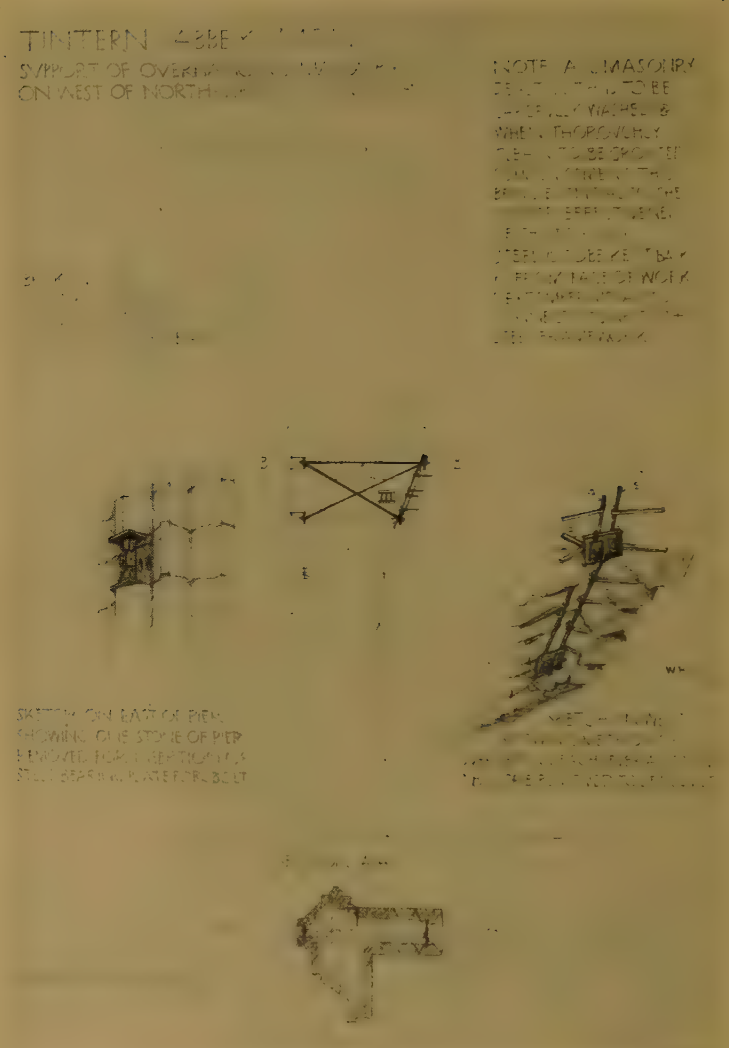

FIG. 71. Original proposal by the author for a "threaded in" scheme of reinforcement. It was not adopted owing to doubts as to its adequate adhesion to the old work.

Architects' Journal," though it is not proposed to make use of it in such a way as would effectively strengthen the thirty-two shattered counterforts, though it will be seen, on reflection, that a hoop which encircles the counterforts and assists in making them perfect and rigid will be a good way of restraining the bulges and permanent enlargement of the drums.

The Commission still does not understand or appreciate Wren's weight-spreading counterforts, and asserts that "these buttresses do not play an important part in transmitting weight to the bastions, nor, in your Commission's judgment, is it desirable that they should." Although not intended as such, this expression of opinion is really an acknowledgment of bewilderment in face of an unfamiliar problem (see Fig. 27 and its accompanying explanatory text).

The counterforts, or "buttresses," are admittedly in a state of advanced disintegration, but they are still exercising highly important functions in minimizing the intensity of the eccentric loading on the piers, and they have probably saved them—and are saving them at this moment—from still more advanced dilapidation and even collapse.

The Commission's inability to agree with me on this point could easily be removed if a few experiments were made in the effects of eccentric loading of masonry structures of arched and vaulted character. By far the most interesting part of the report is that which deals with the Commission's investigations in regard to the periodic movements of the Cathedral under temperature changes. This study is a real contribution to the science of conservation, for although it was known that buildings moved and drifted towards a point from which they would collapse, the part played by temperature changes in this result had not received the attention it deserved. The particulars given in the report should be read in full; though it is not possible to agree with the nomenclature which ascribes the total permanent movement in the

building to the "cumulative effect of temperature changes."

Here, again, the unfamiliarity of the problem has permitted the Commission to confuse the thermal with the gravitational aspect of natural forces, for, while it is eminently proper to recognize the seasonal expansion and contraction of the building as being possibly due to changes of temperature, the permanent expansion in the drums of the dome is due to the interaction of the shape and weight of the building.

That this is so can be recognized without difficulty by persons acquainted with arch and buttress action, or who will make and test models to destruction. Increase of size in the upper parts of a building, whether due to heat expansion or to any other form of pressure implies adjustments in the arch and buttress masses. Contraction due to the removal of the expanding force cannot entirely annul the effects of gravitation upon an imperfectly balanced structure such as are all buildings of ordinary shape, and particularly all masonry structures with arches raised upon vertical supports not chained across the springing.

The Commission's attribution of effects of gravitation to temperature would be merely laughable were it not for the fact that the whole object of the inquiry is to determine a question of weights and pressures such as have been hitherto, by common consent, expressed in terms of gravitational units. And if the Commission is to be allowed to substitute a reference to "the cumulative effect of temperature changes" for a reference to the yielding of material in response to gravitation acting upon imperfectly-buttressed masses, the greater part of the theory of mechanics will have to be re-written.

What really happens is that gravitation is constantly seeking to pull the building down, and accepts the aid of heat expansion, or frost-and-moisture expansion, or any other forces that produce rocking movements. If the dome

expands with heat it should contract with cold, and to explain permanent increase of size one has to look to the ordinary effects of pressure on material. If this were not so, and temperature changes were alone responsible for permanent alterations in shape, why should not these alterations take place in the opposite direction, and knit the building together into an ever closer, stronger, and more united state instead of lowering, loosening, and ultimately destroying it?

The subject cannot be dismissed as a mere question of nomenclature, for the bulges in the drums which occur over the four great open arches can be attributed to the comparative ease with which the light vaults can be spread, while the lesser movements of the drums in the direction of the bastions indicate the more efficient buttressing action of these massive bodies.

Practically all of the deductions from observed facts throughout the report are vitiated by the Commission's failure to appreciate the gravitational and structural reason for the direction of the permanent movements.

Thus the question of the building sliding towards the south is shelved unsolved by the temperature-change hypothesis. "The north to south diameter of the drum was 6¼ in. greater than that from E.N.E. to W.S.W., and it may be reasonably inferred from this and the general shape of the whispering gallery that the expansion between the north and south has been greater than that between east and west, the movement having been towards the south."

This is the sort of reasoning from which Wren and his fellow members of the Royal Society strove so hard to free genuine science, and the analysis of possible settlements in the masonry of the building is similarly defective from the same cause, aided by the tendency to which most inexperienced surveyors yield when confronted with an historical building to investigate. Far too much importance is attributed to historical adjustments in accounting for any deviations from true alignment or from the vertical. "The

original builders made it so" is the exclamation that comes naturally, but incorrectly, in such cases. To quote the report: "In short, the greater part of the tilting observable to-day occurred during construction, and was rectified from stage to stage: the true measure of the subsidence and tilting that has taken place since the completion of the building is the deviation of the base and axis of the lantern from the horizontal and the vertical respectively, and there is no such deviation."

This is a gratuitous assumption that is not necessarily true, for several parts of the building can tilt without the dome and the upper parts of the building being immediately affected. The Commission's own measurements indicate that movements are going on in the drums with a special tendency towards the south, and if the base of the lantern does not tilt for this, why should other movements in the substructures tilt it? How long it takes for a movement of masonry in the foundations to produce its maximum effect at the base of the lantern is altogether unknown, and for a considerable period the reinforced cone of brickwork would continue to act as a rigid support to the lantern, even though one or other of the piers or arches were to settle, slide, or tilt.

The mass of material between the summit of the pier and the base of the lantern would disguise the movement by sharing it imperceptibly among the great number of intervening masonry courses.

A much more complete, exhaustive, and impartial inquiry will be needed before a sound pronouncement can be made in respect of the causes of movement present, recent, and historical, and the periods at which they have taken place.

The history of Dr. Wren's survey of old St. Paul's in connection with proposed repairs, before the fire of London, indicates the manner of commencing such a survey. It also points out the danger of harbouring fixed ideas about the "original builders" and their ways of adjusting matters.

John Evelyn wrote in August 27, 1666: "Finding the

maine building to recede outwards, it was the opinion of Mr. Chichley and Mr. Prat that it had been so built *ab origine* for an effect in perspective in regard of the height; but I was, with Dr. Wren, quite of another judgment, and so we entered it; we plumb'd the uprights in several places."

In the survey of an historical building investigation should proceed from the general to the particular, and to come to the task pinning one's faith upon "precision instruments" is quite on a par with Mr. Chichley and Mr. Prat, who were merely being up to date in attributing to Gothic builders the tricks that Palladio and Bernini had just made famous and fashionable.

A general knowledge gained by actual personal inspection of many vaulted buildings and their natural gravitational drifts would have prevented the ludicrous allusion to the cumulative effects of temperature changes, and so saved the Commission from placing itself in an unfavourable light before the public. When once the general aspect of things has been visualized the more detailed information can be obtained without encumbrance. As it is, the Commission has shown total inability to read the signs of danger in the building or to realize that unless the outward drift of the extremities of the building are controlled by the insertion of reinforcement the buttress action of the walls and bastions will be progressively reduced. The eight main piers are already exhibiting signs of overturning for lack of efficient buttress action, and in view of their comparatively feeble substance and the conditions of application of their excessive load, even the slightest increase in rocking action will dangerously increase their tendency to disintegrate and fail.

The Commission is optimistic, but the optimism seems to be founded upon an inability to understand the language in which the great building expresses its appeal for help. This inability is not surprising; the language of an arched and vaulted building in decay resembles other foreign languages, in that it is a matter for persistent and continued study.

A plan of Tintern Abbey, Fig. 70, accompanies these notes in illustration of the suggested method of attack upon the analysis of an arched structure. The ground plan was first taken in reference to straight setting-out lines, and then the wall tops were measured and drawn in position above it in true relation as determined by a great number of plumb-readings.

The bends and drifts of the upper part of the building were then found to be readable without great difficulty. They conform to a simple definite rule that drifts and movements take place from a strong towards a weak, or from a stable to a less stable part of the building. The most noticeable drift at Tintern is towards the west along the north chancel wall, but this is not because the setting sun, shining down the Wye Valley, has attracted this part of the masonry, but because the fall of the north nave wall has left the great north-west pier of the tower without its proper original buttressing support. The northern corner of the west gable is pulled over to the east by an outcorbelled fragment of some 60 tons weight, so that drifts to the west are not universal or thermal in origin !

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